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AIR DEFENSE
CONCEPTS AND EFFECTIVENESS

by

Jerry Michael Jones
December 1984

Thesis Advisor: R. E. Ball

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Air Defense
Concepts and Effectiveness

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

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December 1984

ABSTRACT

This thesis is intended to become a portion of the textbook to be utilized in the course entitled "Warheads and Lethality" (AE-3705). The text will include an unclassified discussion of the development of anti-aircraft weapon systems intended for defense against hostile manned aircraft and guided missiles. In particular, this thesis discusses the basic concepts, some history, the terminology, and the damage producing aspects of the generic air defense system.

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I. INTRODUCTION

A. WHAT IS AIR DEFENSE?

Air defense is the attempt to destroy hostile missiles and aircraft or to reduce their effectiveness prior to the completion of their designed mission. The primary purpose of air defense is to provide protection for the surface forces. These forces may consist of supply carriers, amphibious units, or vessels deployed for submarine detection or other military or commercial function. The air defense system must either deny the enemy accurate targeting information on any high value units (HVU), cause the enemy to expend resources in order to gain the targeting information, or destroy the enemy prior to their arriving at their maximum weapon release range. These goals can be accomplished through the use of long-range shipboard weapons, including the guns and missiles of sea-based aircraft, of long-range, land-based weapons and aircraft, of short-range, self defense (close-in) weapon systems, of deception techniques, and of evasive tactics.

B. HISTORICAL PERSPECTIVE

1. Early Years

Air defense has developed through the years proportional to the need to counter the current air threat. The earliest forms of air threats were hot air balloons. In the Civil War, hot air balloons were utilized for gathering intelligence on enemy locations and maneuvers. This practice was not particularly appealing because of the high vulnerability of the balloons to anti-aircraft fire. The Navy, on

the other hand, was attracted to this concept in warfare by the possible sea reconnaissance capabilities and the endurance of the balloons. By 1870, balloons were being used to carry messages and as a means of transporting personnel from besieged encampments.

In 1899, the British experimented with man-lifting kites for early warning and intelligence gathering, but with very little success. In the later part of the seventeenth century, a Frenchman, Francesco de Lana introduced the idea of using an aircraft as a weapon. He proposed that one could drop hot pieces of iron on ships, houses, fortresses, and troops with little danger being presented to the aircraft. The idea was rejected as being an unethical means of conducting warfare. In 1903, the Wright brothers developed the first power driven biplane that was equipped for controllable flight. With this invention, machine warfare in the air began to take on a new dimension.

2. <u>World War I</u>

Initially, airplanes and balloons were used in WWI to spot the fall of artillery and for reconnaissance. These aircraft carried no armament and their only measure of self defense rested in their distance from the enemy.

Germany was the first country to utilize aircraft with machine guns for war purposes, and she introduced zeppelins in her raids on England. The bombing attacks were not very successful at the beginning due to poor accuracy, consequently not much interest for air defense was generated. These early aircraft attacks were generally concentrated on war production areas such as ammunition factories, railways, and bridges rather than on weapon carrying platforms such as ships and armies. The war philosophy and policy at this time attributed to the lack of the development of weapon systems to counter the air threat.

3. World War II

After WWI a greater awareness of the vulnerability of surface units and the population centers to air attack was realized. The U.S. Navy conducted experiments to study the feasibility of aircraft attacking ships with bombs and torpedoes. Worldwide philosophy gradually changed to one of acceptance of attacking vital enemy centers as a means of quickly attaining victory. Aircraft could allow an increased measure of security by attacking the enemy's ships and armies while yet far away from their objective, and could be utilized to support armies in overland fighting.

World War II saw numerous advances in air weapons and consequently in air defense strategies to counter these weapons. Germany initialized the "Modern Warfare" by bombing Poland. The Allies became painfully aware of their vulnerability to the German air raids and set out to deal with this new threat. Fighter aircraft were developed to attack the bombers. Improved anti-aircraft guns were manufactured and strategies were introduced to confuse the enemy.

The development of radar brought about a significant change in air defense. Aircraft were more easily detected and at greater ranges than with prior optical instruments. Later, anti-aircraft guns were developed that were slaved to the radars, which provided more accurate aiming of the weapons. Airborne radar also brought about improved navigation for the aircraft and more accurate target identification. One navigation radar development worthy of note was "OBOE", which consisted of two ground based radar systems that provided position information to the attacking aircraft and resulted in more accurate bombing. In this system, an aircraft receiving the two separate radar signals could pinpoint its present location and then fly on a predetermined route to the intended target. The drawback of this

system was that only one aircraft could be guided at a time, and the system was range limited to the radar horizon.

4. Present Day

Because of the continuing improvements in air attack and the introduction of missiles, air defense has become a field of intense development. Faster aircraft, longer range weapons, improved delivery capabilities, and advanced technologies that allow the weapons and the weapon carrying platforms to travel with little probability of detection create severe obstacles for today's defense systems. Presented with these challenges, new advances have occured in early warning systems, and long range anti-air weaponry. Defensive close-in weapon systems that detect and destroy incoming missiles and aircraft without human intervention have been developed and satellites are now employed for targeting and intelligence gathering. Improved electronic warfare techniques identify enemy electronic emissions, provide deceptive measures to confuse the foe and denys the reception of electronic data by unauthorized forces.

Air defense, in the United States today, is primarily patterned as a function of competitiveness with the Soviet Union. Since WWII, the Soviet Union has engaged in tremendous efforts to widen her influence abroad, through the generation of a strong military posture. The Soviet Union's transformation into a global power in a political and military sense began under Khrushchev and has continued under Brezhnev and Kosygin, and its development is expected to continue in the decade to follow.

Soviet policy involves creating a military power that can support a political strategy of worldwide dimension. Perhaps the only controlling factor in this policy is an acute awareness of the destructiveness involved in a nuclear conflict. Because of this concern, emphasis is

placed on the development of a mobile and versatile conventional force. This has been particularly evident in the development of the Soviet Navy. The present growth in Soviet Naval power is probably in response to the "loss of face" experienced in the Cuban Missile Crisis.

Current Soviet policy appears to be one of possessing a better worldwide general-purpose naval capability. There has been a marked increase in sea based aviation platforms, helicopter carriers, and VSTOL carriers. The submarine and surface force capabilities of launching anti-ship missiles has dramatically improved.

Indeed, the Soviet Union has increased its visibility around the world and is a serious competitor in military power. The West has been slow in perceiving these changes in Soviet strength, and as a result has lost the clear superiority it once took for granted. Air defense systems must continue to improve to contain the new aircraft-capable Soviet Navy. These systems must be prepared to deal with numerous high speed missiles and aircraft, weapon-carrying helicopters, modern electronic warfare devices, and the advances in weapon delivery techniques.

C. AIR DEFENSE TERMINOLOGY

In order to become proficient in air defense analysis and design, one must become familiar not only with the specific threats, but also with the proper usage of generic terms and the various terminology concepts. The major subfields that comprise the air defense topical field are shown in Figure 1.1. This topical field contains those subfields which are used to describe the weapon characteristics, the operations and the lethality. Weapon characteristics refer to the type of weapon, such as anti-aircraft

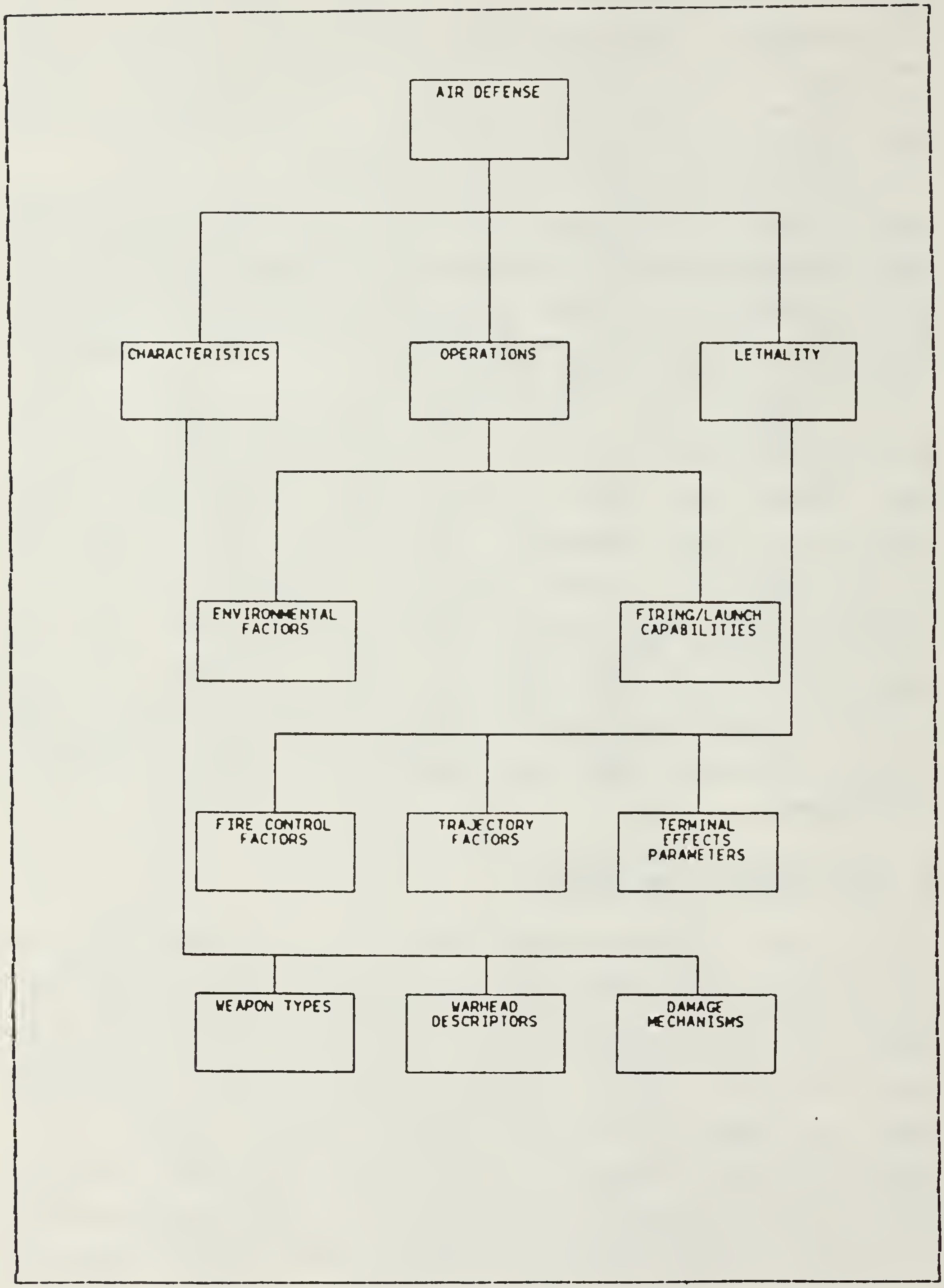

Figure 1.1 Air Defense Topical Field

artillary or surface-to-air missiles, the warhead descriptors, such as armor-piercing or shaped charge, and the associated damage mechanisms, such as blast or fragments. Operations refers to those inherent capabilities and environmental factors which relate to the ability of the defense system to perform its basic firing/launch functions. For example, environmental factors include threat mobility, locational adaptability, and weather capability. The firing and launch capabilities include slew rate, rate of fire, and intercept envelope. Lethality refers to those factors which relate to the fire control, trajectory, and terminal effects of the weapon in the process of directing, projecting, and activating damage mechanisms toward the target. Fire control factors consist of items such as aiming error, lead angle prediction, and tracking error. Trajectory factors include ballistic dispersion and gravity drop. The terminal effects parameters include projectile caliber, equivalent weight of TNT, and fragment density.

The terms above do not reflect any interaction between the damage mechanisms and the target. The descriptors relate to to the inherent capabilities of the air defense system. The System Response topical field, shown in Figure 1.2 contains those terms which are used to describe the interactions of the damage mechanisms and the target, i.e., the damage processes. Damage processes are phenomena such as penetration and blast loading. This field also contains the target lethality criteria, which define the conditional response of the target to the damage processes, and the response measures, which are quantitative measures of the interaction between the damage mechanisms and the target.

The assessment of the lethality of an air defense system against a particular air target involves the combination of the air defense topical field and the system response topical field. The connection between the air defense

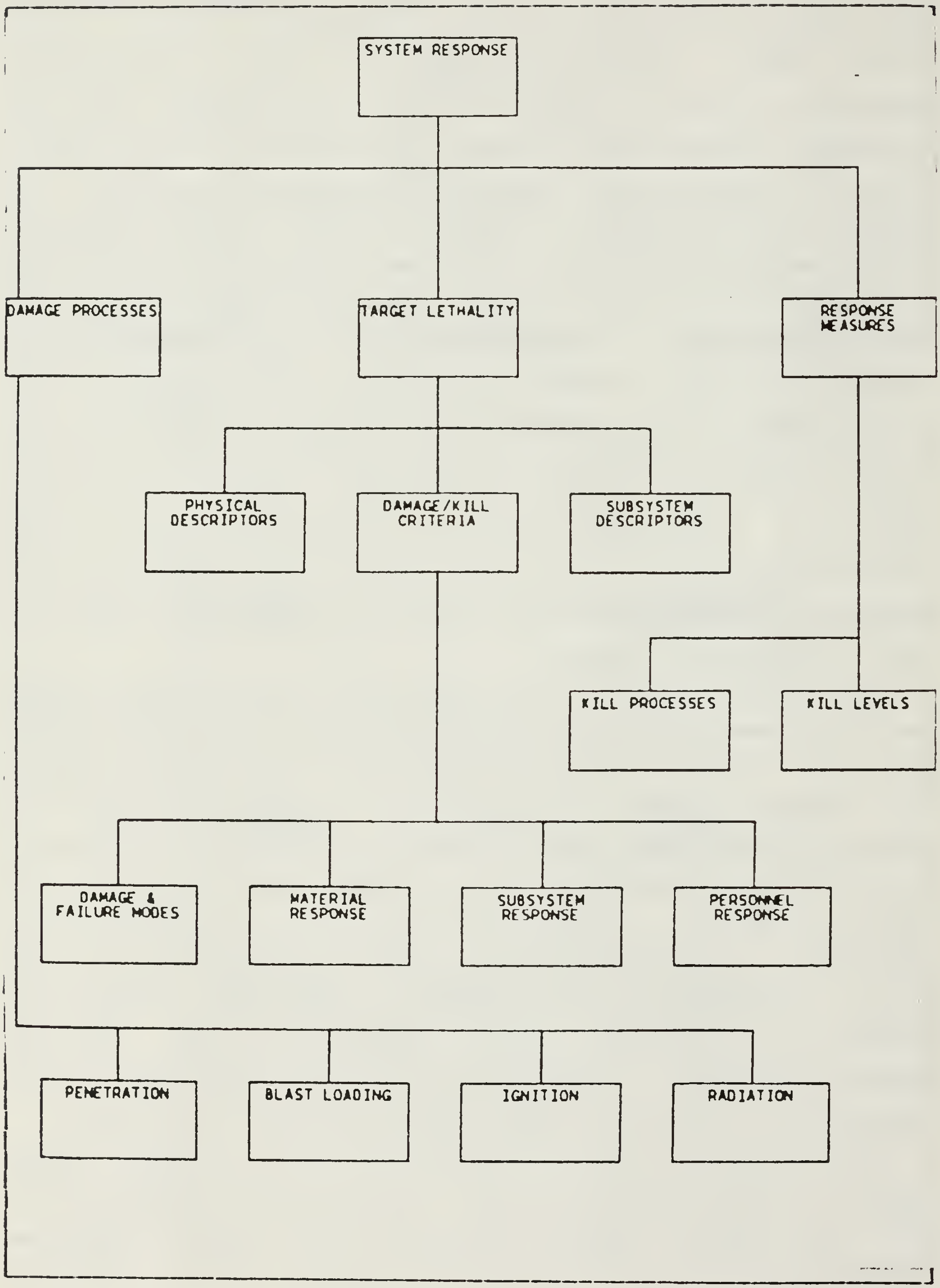

Figure 1.2 System Response Topical Field

topical field and the system response topical field is often difficult to grasp because of the misuse of many of the terms and concepts. The dotted line in Figure 1.3 connecting the damage mechanisms, the terminal effects parameters, and the damage processes subfields illustrates one of the more confusing connections. Figure 1.4 gives a comparison of example terms in these three subfields which in the past have been commonly, but erroneously, interchanged, with resulting ambiguity.

D. WEAPON CHARACTERISTICS

The weapon characteristics of interest here are those descriptions that relate to the weapon type, the warhead type, and the damage mechanisms. The warhead type and damage mechanism characteristics will be covered in detail in Chapter III.

1. Weapon Types

Weapon type denotes the general classification of the weapon element in terms of firing platform and site type. In general, weapon elements can be grouped into two types: terminal and non-terminal, as shown in Figure 1.5.

The non-terminal weapons do not in themselves possess a capability to inflict damage. They are the electronic and/or optical systems used to support the terminal weapon elements. These elements normally consist of detection and early warning, target tracking,electronic countermeasure (ECCM), fire control, and communication systems. They can be land-, sea-, or air-based and are normally an integrated part of the air defense's force. Their purpose is to supply target position, speed, and heading information to the terminal weapon units.

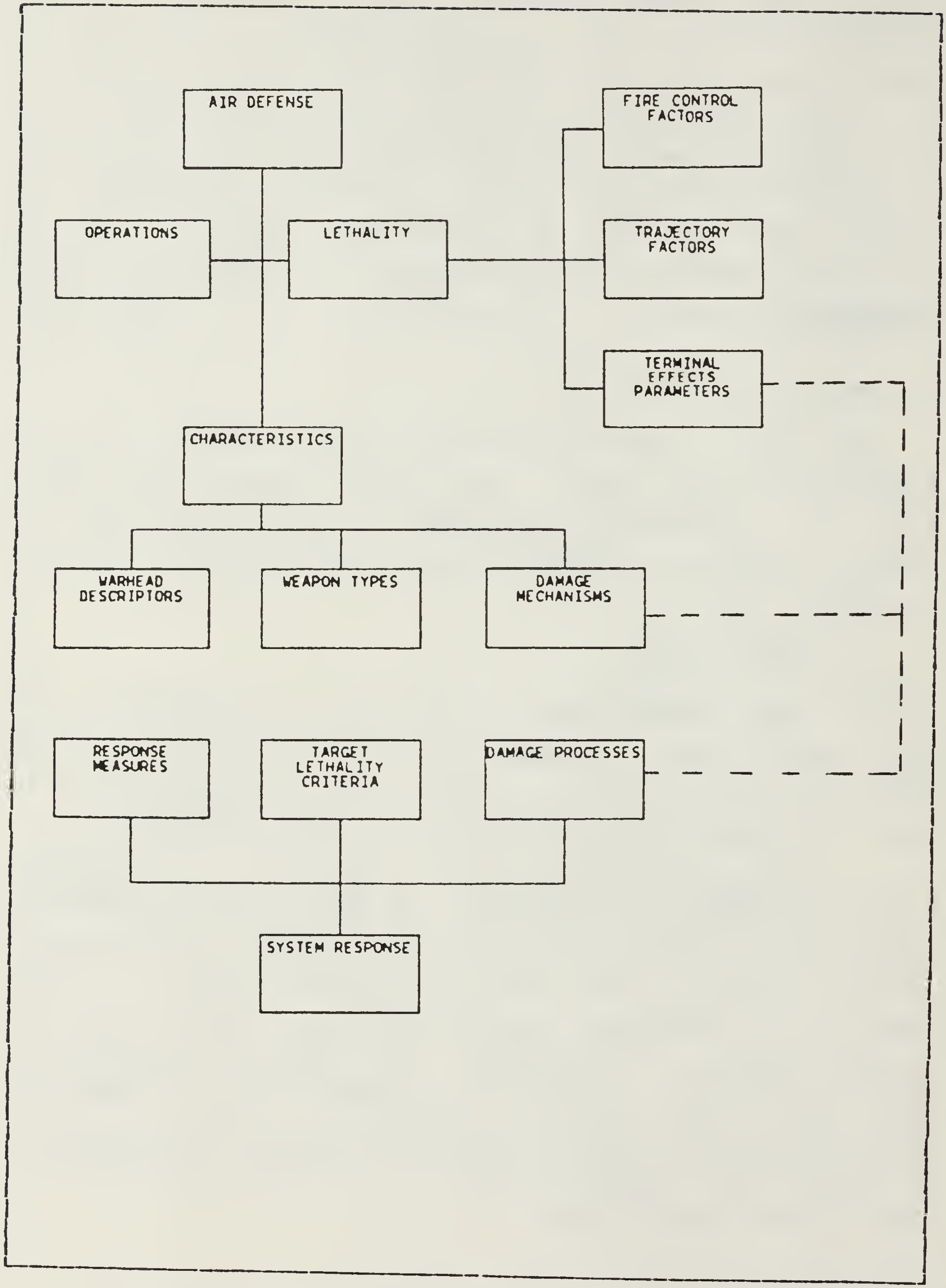

Figure 1.3 Connection Between the Air Defense Topical Fields

SUBFIELD	KEY CONCEPTS OF DEFINITION	EXAMPLE TERMS
DAMAGE MECHANISMS	NATURE OF THE WARHEAD OUTPUT	PENETRATOR INCENDIARY PARTICLES ELETROMAGNETIC FLUX BLAST ACCELERATED ELECTRON
TERMINAL EFFECTS PARAMETERS	INTENSITY OF THE DAMAGE MECHANISM OUTPUT	PROJECTILE CALIBER INCEN. FLASH DURATION ENERGY BEAM INTENSITY EQUIV. WEIGHT OF TNT ELECTRON-VOLTS
DAMAGE PROCESSES	INTERACTIONS BETWEEN DAMAGE MECHANISM AND TARGET	PENETRATION IGNITION TEMPERATURE RISE BLAST LOADING VAPORIZATION

Figure 1.4 A Comparison of Example Terms

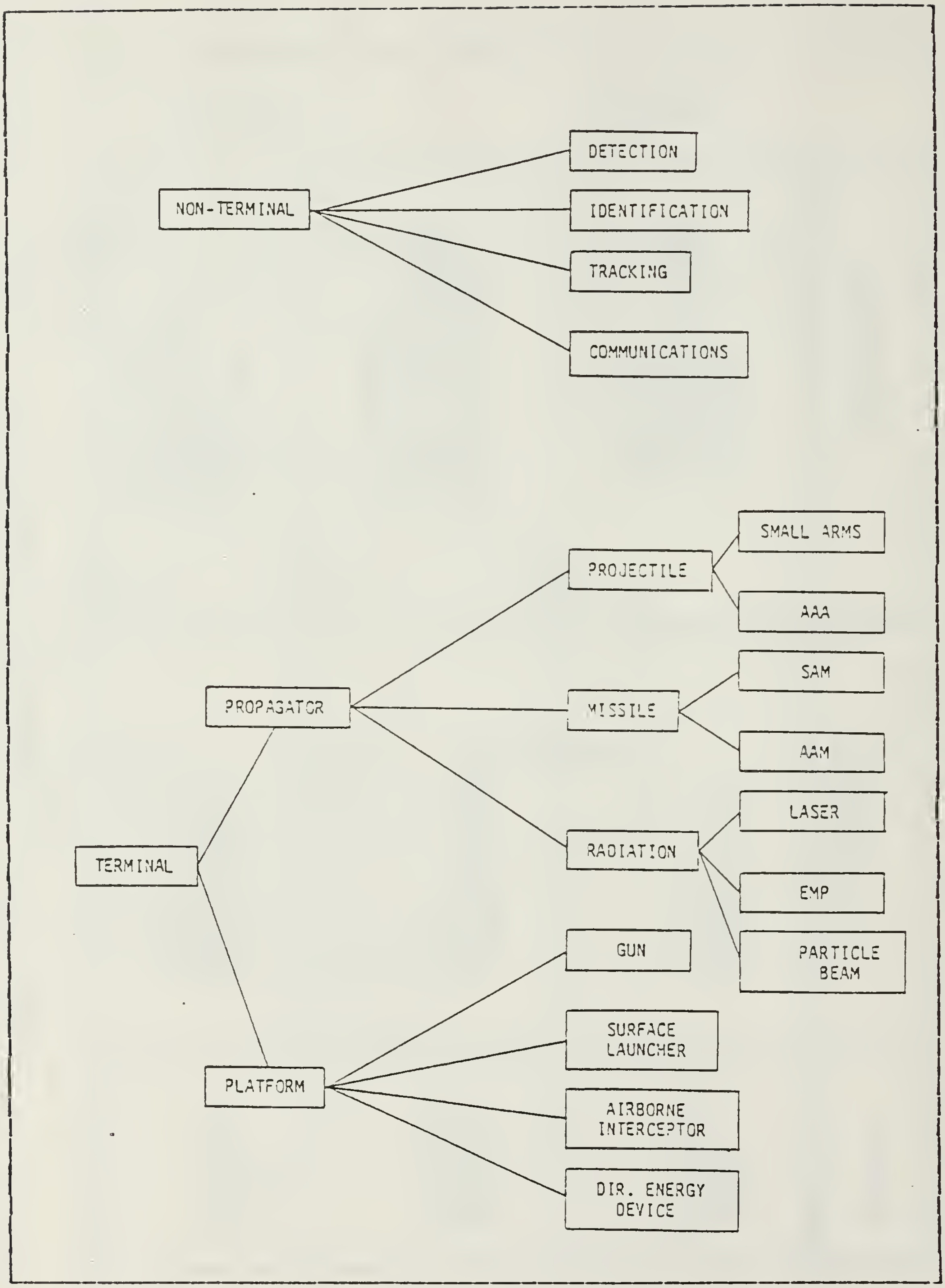

Figure 1.5 Weapon Types

Terminal weapon elements have the capability to cause damage to the airborne target. They consist of the firing platform and the weapon propagator.

2. Firing Platforms

Terminal weapon platforms are divided into four categories: guns, missile launchers, airborne interceptors, and directed energy devices.

a. Gun

A gun is a device, including any stock, carriage, or attachment from which projectiles are propelled by the force of an explosive reaction. It includes weapons of various sizes ranging from hand-held small arms to much larger transportable or stationary anti-aircraft artillery (AAA).

b. Surface-to-Air Missile (SAM) Launch and Guidance Equipment

This surface platform is used to launch and guide SAM's to an intercept point. SAM launch and guidance equipment varies in size from a single hand-held launch tube to a semi-permanent complex containing numerous compartments of equipment and launch units. The system may employ both optical and radar target tracking in conjunction with special missile tracking and guidance computers.

c. Airborne Interceptor(AI)

This is a high performance, highly maneuverable aircraft designed to engage the aircraft and destroy air targets. Weapon systems employed by the airborne interceptor include air-to-air guns, missiles, and the associated equipment for identifying, tracking and firing the weapons.

d. Directed Energy Device

Weapon systems which produce a beam of electromagnetic radiation with intensity sufficient to damage a target are called directed high energy weapons (DHEW). In addition to melting or thermally degrading portions of the target, these weapons may do more subtle damage by overloading or blinding the various electromagnetic and optical sensors on the target.

3. Weapon Propagators

Weapon propagators are divided into three categories: projectiles, guided missiles, and radiation.

a. Projectiles

A projectile is an object initially propelled by an applied exterior force and continuing in motion by virtue of its own inertia, as a bullet, bomb, or shell. The term projectile is generally used to represent the device containing the warhead. This propagator is usually associated with small arms and AAA.

Small arms are guns that fire projectiles up to and including 14.5mm in diameter. The term small arms is generally used to denote guns with calibers 7.62mm (30 cal), 12.7mm (50 cal), and 14.5mm. These weapons usually employ visual or optical tracking and are fabricated in differing barrel configurations, usually one to four. Most projectiles fired by these weapons are of the ball (B), armor-piercing (AP), or armor-piercing-incendiary (API) type, except for the 14.5mm machine gun which is also capable of firing a high explosive incendiary (HE-I) and an incendiary tracer (I-T) projectile. Figure 1.6 shows a typical AP-I projectile.

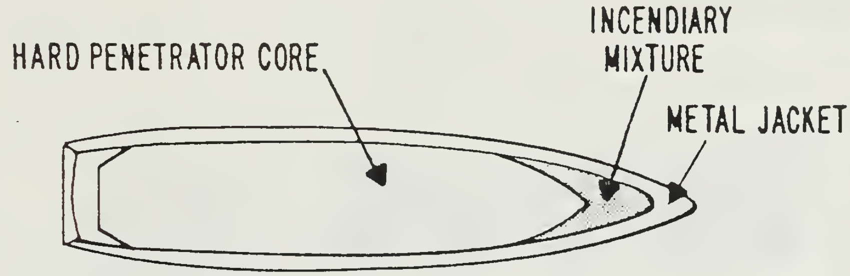

Figure 1.6 Typical AP-I Projectile

AAA denotes that category of guns that fires projectiles greater than 20mm in size. (The entire group of automatic weapons larger than 12.7mm is also referred to as anti-aircraft or AA guns). AAA is generally standardized to calibers 23mm, 30mm, 37mm, 57mm, 85mm, and 100mm, although there are some types with calibers greater than 100mm. The projectiles are either high-explosive (HE) or armor-piercing (AP), and they may contain incendiary (I) and/or tracer (T) material. Figure 1.7 shows a 23mm HE-T projectile. The guns that fire these projectiles may be land-, sea-, or air-based and may employ either optical or radar tracking, or both. Like small arms, AAA may have either single- or multiple-barrel configurations.

b. Guided Missiles

A guided missile is an aerospace vehicle, with varying guidance capabilities, which is self-propelled through space for the purpose of inflicting damage on a

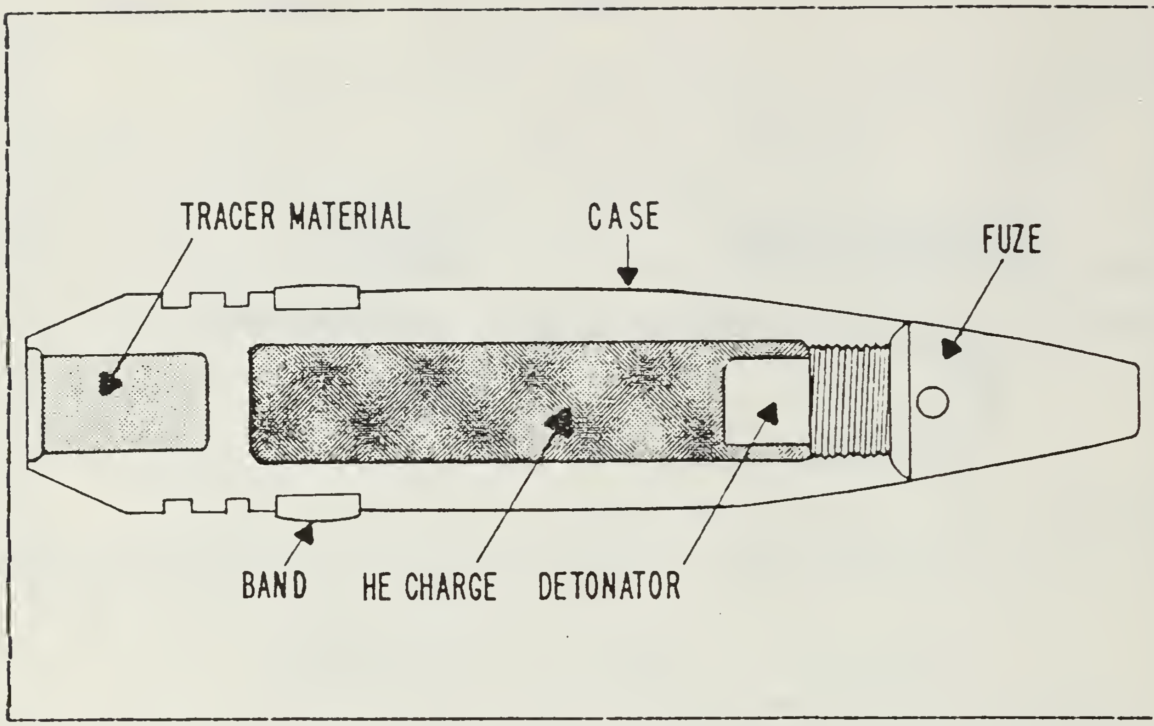

Figure 1.7 HE-T Projectile

designated target. (An unguided missile is called a rocket and is normally not a threat tc airborne aircraft.) These propagators contain a propulsion system, a warhead section, a guidance section, and one or more sensors. Movable control surfaces are deflected by commands from the guidance section to direct the missile in flight. Some missiles are dependent on off board equipment for guidance commands, while others are able to guide themselves independently after launch. The various kinds of missile guidance will be discussed in Chapter II. A sketch of a typical missile configuration is given in Figure 1.8. The two types of missiles that pose a threat tc airborne aircraft are the air-tc-air or air-intercept missile (AAM or AIM) and the surface-to-air missile (SAM).

Air-to-air missiles are launched from interceptor aircraft. Although they may employ various guidance

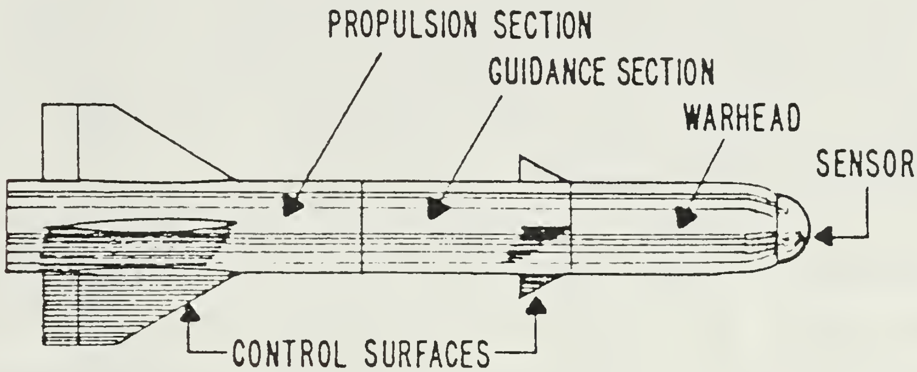

Figure 1.8 Typical Missile Configuration

techniques, some form of homing is the primary type of guidance used due to weight constraints in the launch platform. Weight constraints in the missile itself dictate the use of relatively small warheads.

Surface-to-air missiles are those launched from land- or sea-based platforms. They have varying guidance and propulsion capabilities which influence their launch envelopes relative to the target. They employ various, and in many cases sophisticated, electronic counter-countermeasure schemes to enhance their effectiveness. Because weight is not as much of a constraint for the SAM's, these missiles are often much larger than their air-to-air counterparts, and they can have larger warheads and ranges.

c. Radiation

Radiation is energy transmitted as either particles or waves through space at the speed of light. Radiation is capable of inflicting damage when it is transmitted toward the target either in a continuous beam or as a high-intensity, short duration pulse. Weapons utilizing radiation as the propagator are referred to as directed high energy weapons (DHEW) and are predicted to become operational within the next decade.

There are three types of radiation that are propagated by the DHEW. They are the coherent electromagnetic flux, the noncoherent electromagnetic pulse (EMP), and charged nuclear particles. The coherent electromagnetic flux is produced by the High Energy Laser (HEL). The HEL generates and focuses electromagnetic energy into an intense concentration or beam of coherent waves which is pointed at the target. This beam of energy is then held on the target until the absorbed energy causes sufficient damage to the target to result in its eventual destruction. Radiation from a laser that is delivered in a very short period of time with a high intensity is referred to as a pulse-laser beam. The acronym laser stands for Light Amplification by Stimulated Emission of Radiation.

A noncoherent electromagnetic pulse, or EMP, consists of an intense electronic signal of very short duration that travels through space like a radio signal. When an EMP strikes an aircraft, the electronic devices in the aircraft can be totally disabled or destroyed. The effects of EMP were first observed and measured during the high altitude nuclear testing that took place in the early 1960's, and since that time EMP has generated considerable interest and concern. In the past, EMP of sufficient energy to qualify as a threat has been generated only by nuclear

detonation. Aside from the very real threat, however, present technology trends indicate that nonnuclear weapons capable of sufficient power to generate a real EMP threat to aircraft may become operational within the next decade.

The charged particle beam weapon is the newest of the developing threats and utilizes radiation in the form of accelerated sub-atomic particles. These particles, or bunches of particles, may be focused on the target by means of magnetic fields. Considerable target damage can result. This type of weapon has the advantage that it will propagate through visible moisture which tends to absorb energy generated by the HEL.

E. THE BIG PICTURE

The sequence of events in an encounter between an air defense system and an air target is referred to here as the big picture. This text will present air defense as viewed from a typical task force. This generic formation will consist of a single high value unit (the aircraft carrier) supporting aircraft, and several ships with medium range missiles and anti-aircraft guns. Although utilizing a task force viewpoint, it should be noted that these basic concepts of air defense may apply to any air defense role.

The scenario shall begin with the detection of an unknown aircraft approaching the formation. Suppose, for example, a single air contact is detected by radar and then tracked continuously to aid in gaining its identity and determining its flight parameters.

If the target's identity is unknown or evaluated as hostile, then the contact will be assigned to a fire control system for accurate tracking. A particular weapon type, in this case a missile, is selected and the weapon is prepared for delivery. The fire control system shall compute launcher

orders, intercept data, missile commands, and may present reccomendations to improve the probability of gaining a target kill. The missile is then fired, and guided to its predicted intercept point. Upon intercept the missile is commanded to explode via fuzing action, and the damage mechanisms will be delivered to the target. The firing unit must then evaluate the results of the shot, and if needed additional action may be required to destroy the target. The scenario to be considered is that the task force is to defend itself against air targets using gun systems, missile systems and the associated air defense equipment. The entire scenario from detection to destruction of a hostile aircraft will now be considered in more detail.

II. OPERATIONS AND LETHALITY

As stated previously, air defense consists of three broad areas; Characteristics, Operations, and Lethality. The Operations field consists of those environmental factors and inherent capabilities that relate the ability of the air defense system to perform its basic functions. The Lethality field refers to the collection of factors that relate to the fire control, the propagator trajectory, and the terminal effects parameters.

A. INHERENT OPERATIONAL CAPABILITIES

The sequence of events in almost any encounter between an air defense system and its target is somewhat the same. There are six distinct phases incorporated in the inherent capabilities of the air defense system; Search and Detection, Track and Evaluation, Fire Control Acquisition and Track, Launch/Firing, Trajectory and Guidance, and Final Evaluation. Figure 2.1 illustrates a typical pattern of events that may occur in an air defense encounter.

1. Search and Detection

For any air defense system to function, it must first be able to detect the presense of aircraft at a range that will allow enough time to evaluate the possible threat and to deliver weapons to counter the threat prior to the aircraft accomplishing its objective. The threat can be guided or unguided. It may be maneuverable or may fly on a preset path. It may travel at high altitudes or just above the surface, and it may travel at subsonic or supersonic speeds. The detection system must be able to sense the

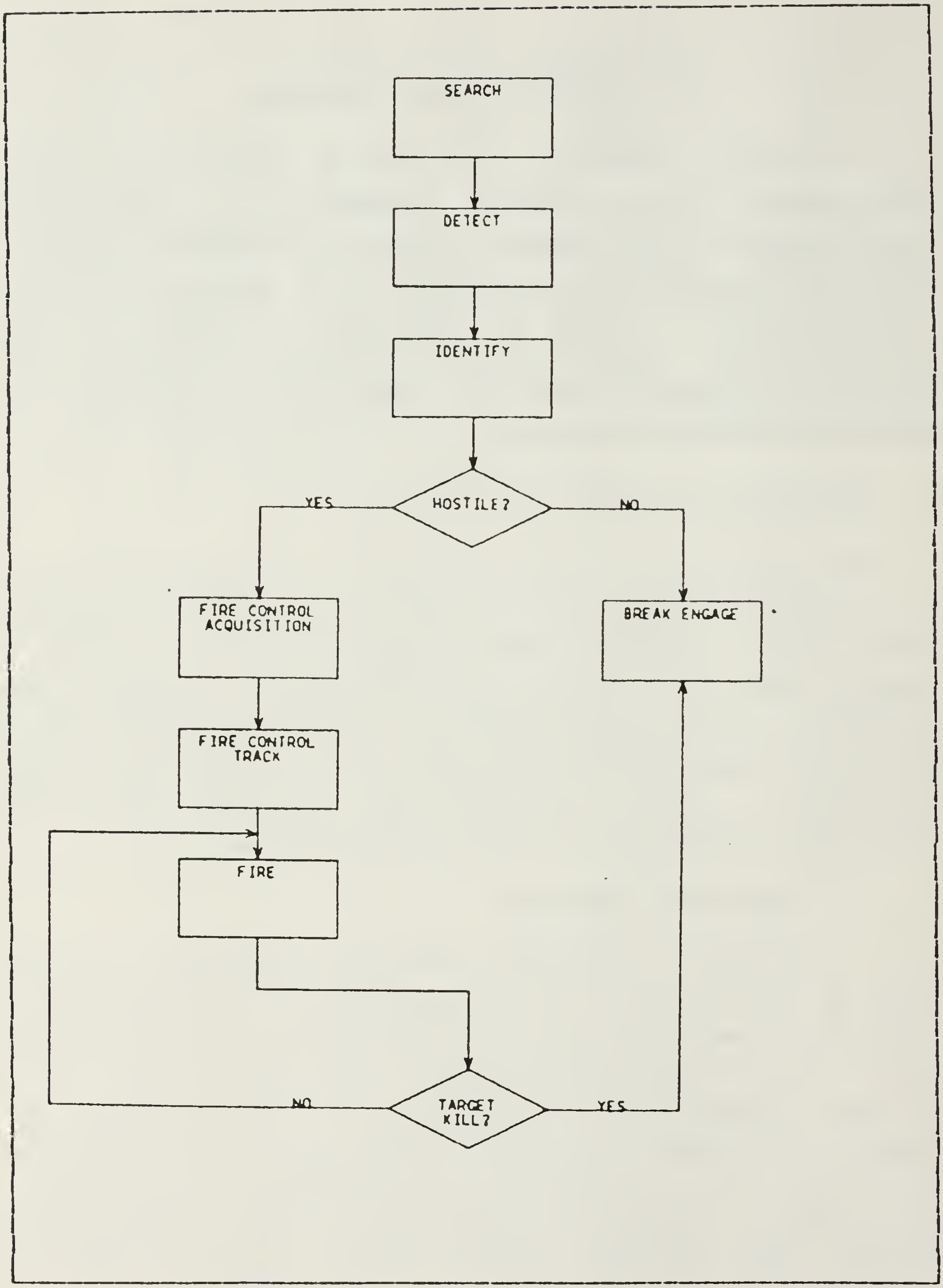

Figure 2.1 Operations Flow Chart

presense of the threat and to provide the necessary data to enable the determination of the threat's capabilities within this wide spectrum.

Search and detection can be accomplished by radar, by the human eye (with or without the assistance of optical or electro-optical devices), by the human ear (aided or unaided), by lasers, and by forward looking infrared devices (FLIR). There are three phases involved in the search and detection for aircraft. The first is the surveillance of an assigned area to determine the presense of targets. Second, target parameters such as speed, number of targets, and heading are determined. The final phase consists of determining the target's location in range, bearing, and elevation.

There are three general detection methods utilized. The first is an active system. It employs a self-generated source as the sensing agent. For example, a radar is an active system because it transmits a self-generated electromagnetic beam which reflects from the target to the radar receiver. The second method is a semi-active system, which has the agent to be sensed (radiation) transmitted from a source separate from the detecting system. Finally, a passive detection system is one in which receives a signal that is generated by the target itself. An example of a passive system is one that detects the infrared radiation emitted from the target's heat transmitting areas, such as hot engines.

There are several factors that may hamper the detection of targets. Some possible sources of detection error may include electronic and thermal noise, radar array misalignment, servo or mechanical vibration, target glint, target scintillation, atmosphere propagation, and clutter. Noise, either internal to the sensor or generated in the environment surrounding the target, may obscure the presense

of valid targets. Detection systems must be designed to minimize internal noise and alsc to distinguish signals from ambient or external noise. Other factors affecting the detection of valid radar targets includes the target radar cross-section, the radar transmitter power, the receiver sensitivity, and operator performance. Countermeasures, such as jamming and deception techniques, may be employed by the enemy to confuse a normally reliable system. The detection system must be equipped to use counter-countermeasures to bypass the effects of enemy electronic warfare tactics. Among these counter-countermeasures are frequency diversity, increasing transmitter power, increasing receiver sensitivity, and anti-jam features such as antenna side lobe cancellation and Moving Target Indicator devices.

2. Track and Evaluation

The air defense system's task has only begun with the detection of air contacts. Each aircraft detected must be tracked accurately to provide data for evaluation purposes and to allow the more sensitive fire control radar to locate the target. The evaluation carried out on the aircraft determines if the aircraft is friend, foe, neutral, or unknown. This decision must be made as quickly as possible to maximize the weapon firing time. One such technique is Identification Friend cr Foe (IFF), which employs an antenna to send an "interrogation" signal to all aircraft detected. Friendly aircraft have equipment on board which automatically re-transmits a signal that identifies the aircraft. Without the returning signal, the surface unit must make a decision as to the classification of the contact. The decision can be made based on possible emissions received from the aircraft, the flight profile of the aircraft (low, high, fast, slow), the composition of the threat aircraft (one,few,many), and the course the aircraft

is taking (crossing, closing, opening). The present tactical situation may also aid in the evaluation of the aircraft. For example, if no hostilities are present and the surface unit is not in a wartime environment, then a single air contact may be assumed friendly even though no IFF is received. If, however several aircraft are detected closing at a high rate of speed and there is a hostile environment, then the aircraft may be assumed hostile provided no evidence to the contrary exists. Precautions should always be employed, and readiness of an air defense system should be exercised to ensure that proper tracking and evaluation techniques are utilized to their fullest.

Figure 2.2 illustrates a possible sequence of events from detection of an aircraft through the evaluation and engagement decision processes. Without any identification method, the flowchart leads to a block entitled "Apply Doctrine". The firing doctrine should address in detail the procedures in handling unidentified contacts. In particular, the firing doctrine may consider such questions as; is the aircraft in a Weapon Free or Weapon Tight area, is the aircraft committing a hostile act, and is the aircraft penetrating the defense corridor? The firing doctrine will be discussed in greater detail later in this chapter.

3. Fire Control Acquisition and Track

It is not enough to just detect, track, and classify targets. Hostile aircraft that are to be engaged with anti-air weapons must be tracked with a high degree of accuracy. This accurate tracking is necessary to determine launching orders, intercept positions, aiming point, and position data for missile seekers to look for valid targets, and to determine continuous updates to the solution of the fire control problem. The accurate tracking is accomplished by the fire control system.

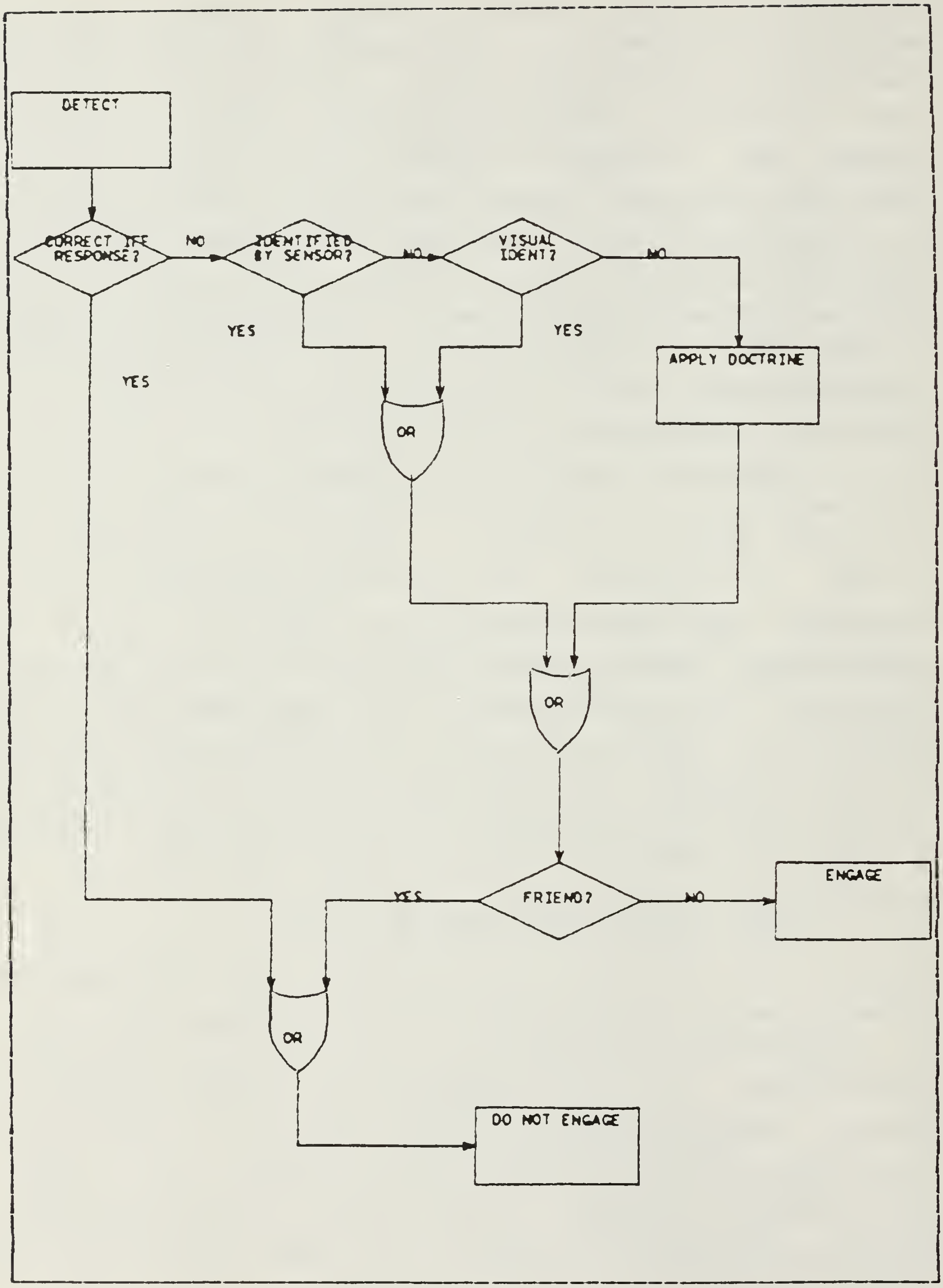

Figure 2.2 Evaluation and Engagement Flowchart

a. Fire Control Factors:

Fire control factors consist of the types of fire control, the types of coverage, and the types of errors. The usual types of fire control are an open sight, an on-mount optical or mechanical lead computing sight, radar, and electro-optical. Small arms and light AAA typically use the open or on-mount sight, whereas most heavy AAA and the guided missile systems use radar and/or a direct view optical or electro-optical device. The types of coverage are aimed fire (at a specific target), sector intercept (fire directed to a sector of air space), barrage (general coverage of the air space), and any combination of these. There are three major types of fire control error: tracking error, aiming error, and lead angle prediction error.

Tracking error is the error introduced into the firing or launch and guidance operations of a weapon system by the inability of the tracking system to provide an exact record of the aircraft flight path. Tracking data is used for many purposes, such as alerting appropriate threat units,establishing tactics, establishing lead angle information for weapon firing, and propagator guidance. Therefore the source and magnitude of tracking errors are very significant in weapon effectiveness. The term tracking error is used to represent the net effect of all contributors or sources in specifying target position and rate data.

Aiming error is the error introduced into the firing or launching operations due to the inability to correctly position or aim the appropriate equipment in a desired direction. Aiming errors are used to represent errors involved in pointing or positioning a weapon or weapon platform at the desired point predicted by the fire control system. These errors may stem from a human interface, from a machine, or from a combination of both.

Lead angle prediction is that fire control computational process used to establish the desired positioning or aiming information. All weapons that fire ballistic projectiles must have some means of solving the fire control problem. From the measurement of current target position and velocity, the future target position must be estimated, weapon aim angles determined and fired so that the projectile and the target will arrive at the predicted intercept point simultaneously. Most prediction methods use a linear extrapolation of the target's trajectory (assuming a constant velocity) to estimate the future target position. Lead angle prediction error is the projectile miss distance resulting from errors in the prediction of the target flight path. Prediction errors may be the result of unexpected or evasive target maneuvers (jinking) during the flight time of the projectile or due to limitations in the process used to predict future target position. The prediction error for any firing situation is usually defined as the minimum distance from the predicted intercept point to the target's actual position at the time of intercept.

A typical fire control system consists of a radar and a computer. A contact that is classified as hostile or unknown may be assigned to a fire control radar. The fire control radar will slew its beam to a point in space that the search radar has designated as the target's position. If the target is not displayed by the fire control radar at the designated position, then a search is initiated. The search is a calculated pattern designed to optimize the probability of detection of the target. The accuracy of the target location designations to the fire control radar will be a function of the experience and accuracy of the search radar operator. After the target is acquired, tracking is accomplished either automatically or manually. Tracking provides continuous accurate data of the

target to the fire control computer which calculates various launch parameters for the weapon, such as seeker orders, intercept position, intercept time, maximum and minimum ranges, and operator recommendations.

b. Fire Control Parameters:

Some important fire control parameters are discussed below.

(1) Initial Reaction Time. This is the time interval which elapses between the time an air defense system is made aware of a need to be fully operational and the time the system is ready to begin its normal operational mode against the target aircraft.

(2) Maximum Slew Rate. This is the maximum angular velocity in both azimuth and elevation at which the tracking carriage can be rotated in order to begin tracking and engaging an aircraft. The parameters which determine the maximum slew rate include the mass of the equipment to be rotated and the electrical, mechanical, or hydraulic power available to rotate the equipment.

(3) Maximum Target Detection Range. The maximum target detection range is that range at which a target can barely be unambiguously discerned. It is often expressed numerically with respect to a target signature of a standard size. For example, the maximum detection range of a radar is generally given for a target with a one square meter radar cross section.

(4) Acquisition Time. This is the elapsed time from the alert to the time the tracker has acquired the target.

(5) Maximum Tracking Rates. These are the maximum rates in azimuth and in elevation that the tracking carriage can be rotated while measuring the aircraft's position versus time.

4. Launch / Firing

The decision to fire or launch a weapon should be in accordance with the firing doctrine of the air defense forces. The doctrine must address several elements to be considered by the firing unit in a typical hostile encounter. These elements include own force capabilities, hostile force capabilities, and the firing policy.

a. Own Force Capabilities:

(1) Weapons Available. Prior to engaging any enemy target, the coordinating person or persons should be knowledgeable in the type and quantity of weapons available, as well as the capabilities, advantages, and disadvantages of each.

(2) Position of Own Forces. The position of supporting forces is extremely important in assuring the best defensive posture is achieved. For example, if the threat is anticipated from a particular direction, called the threat axis , then the defending forces may be positioned in such a way as to offer the maximum protection to the HVU.

(3) Launch Rate and Rate of Fire. The rate of fire is the number of projectiles per unit time that can be fired. This term is primarily used as a measure for small arms and AAA. Launch rate is a similar term which is used in connection with the number of missiles that can be launched per unit time. The launch rate is dependent upon the capability of the equipment to reload the launcher with the appropriate weapon type, applying warm up power if required, and supplying accurate target data to the weapon directing devices.

(4) Muzzle Velocity. This is the velocity of the projectile with respect to the muzzle at the instant the

projectile leaves the barrel. This velocity is a function of the projectile weight, firing charge, and barrel characteristics.

(5) Maximum Firing Range. This is the greatest distance that a weapon can be delivered from the firing or launching platform. The maximum firing range is dependent on environmental factors such as wind and density and on the weapon characteristics such as size, shape, weight, and type of propellant.

(6) Firing and Intercept Envelopes. The firing envelope is defined by the locus of points that represent the current prediction of the aircraft's position when a projectile or missile can be launched with the expectation of achieving an intercept. The intercept envelope is similar to the firing envelope except that the locus of points now represents the location of the aircraft at the time of intercept. The firing envelope includes the tracking time required before a launch can occur. A typical missile firing envelope is shown in Figure 2.3. Maximum range denotes the position of the aircraft when the launch occurs corresponding to the maximum distance the missile can reach and cause damage to the aircraft. The maximum launch range depends on the target speed or Mach number and is obviously shorter for receding aircraft than it is for approaching aircraft. The requirement for damage is often specified in terms of a missile miss distance, which is the closest point of approach of the missile to the target. It may also be expressed in terms of a minimum level of missile maneuverability available or by the maximum time of missile flight based upon the self-destruct time set in the fuze. The maximum range at intercept is referred to as the maximum effective range. The dead zone is that volume of space around the launcher in which the missile warhead is unarmed as the missile passes through. The missile limit boundaries

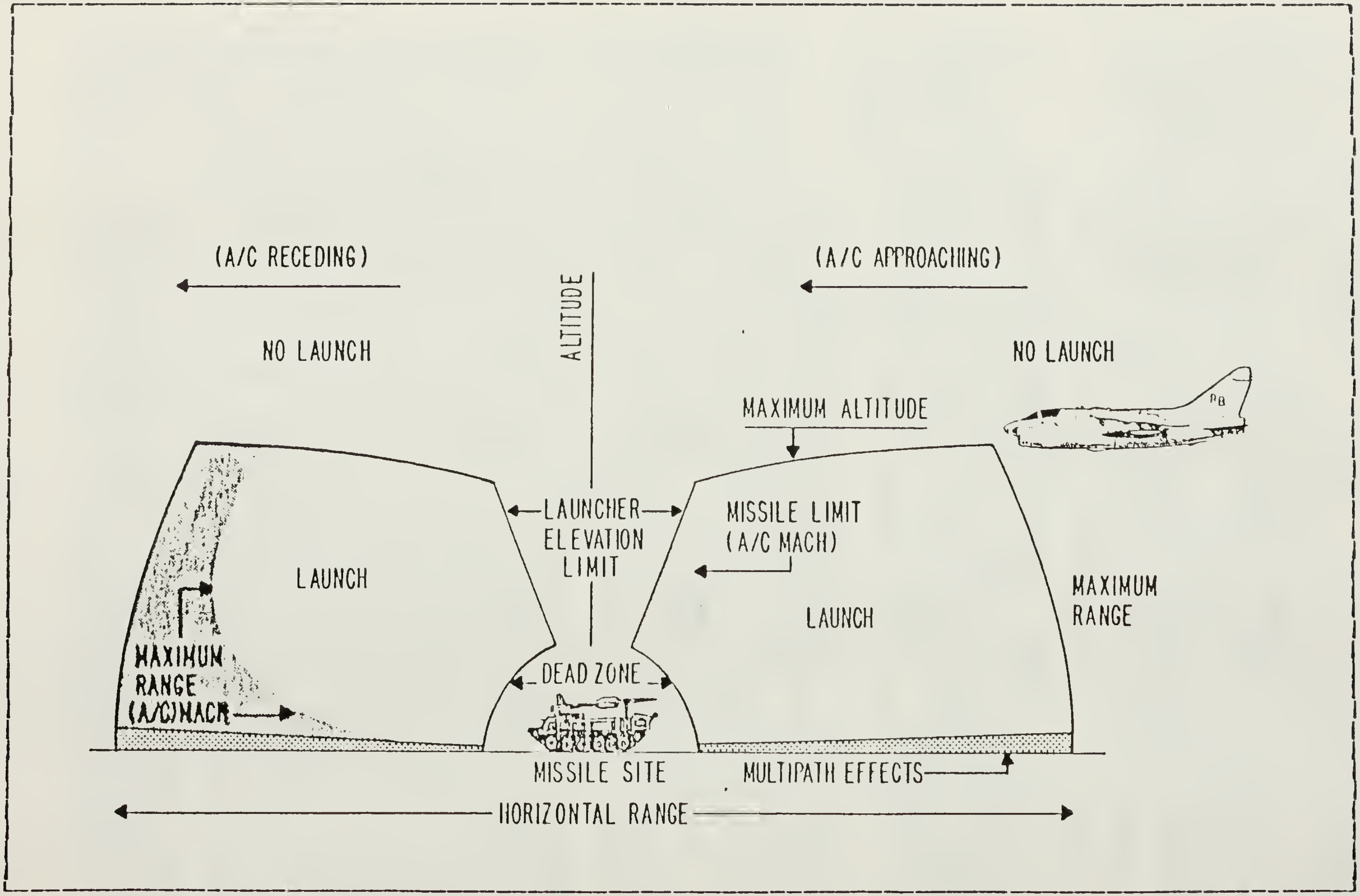

Figure 2.3 Typical Missile Envelope

are a function of the aircraft direction, speed, maneuvering, and rate limitations on the missile and its components. Multipath effects refer to that region where electromagnetic tracking beams reflect from the terrain or surface to and from the aircraft. Tracking accuracy may be severly degraded in this region.

b. Capabilities of the Enemy:

The decision to engage aircraft should be accompanied with a great deal of consideration of the enemy's capabilities. Knowledge of these capabilities may be limited depending on accurate targeting data, up-to- date intelligence reports, and operator expertise. Some of these considerations are the threat type and quantity, the position of the threat in relation with friendly forces, closing rate, and the maximum weapon release range of the opposing forces.

c. Firing Doctrine:

The firing policy of the air defense systems should provide information as to the optimum utilization of weapons in a hostile encounter. The policy should discuss the positioning of forces to maximize their weapon coverage, and the number and type of weapons to be fired may be dictated. For example, the situation may call for rapid anti-air gunfire, a single missile salvo, or perhaps for a shoot-look-shoot policy. Shoot-look-shoot is a firing doctrine in which one missile is launched, and a second missile is subsequently fired if the first missile fails to destroy the target. Other variations may include a shoot-shoot-look-shoot, or ripple firing, which calls for rapid firing of several weapon types. Other considerations in the firing decision should include current performance reliability of weapon supporting equipment, strength of the track, and the force mission.

5. Trajectory and Guidance

a. Trajectory Factors:

After a weapon has been fired, various trajectory factors influence the path of the weapon from the firing platform to the target. These factors can be divided into two categories, those associated with non-guided propagators and those associated with guided propagators.

Non-guided propagators are projectiles and directed radiation. Some of the factors that affect the trajectory of these propagators are discussed below.

(1) Gravity Drop. Gravity drop is a measure of the displacement of the flight path of a ballistic projectile attributable to the force of gravity. The gravity drop is proportional to the time of flight and can be approximated by $(1/2)gt^2$ where g is the gravitational force and t is the time of flight.

(2) Ballistic Dispersion. This is the scatter of impact points of projectiles about a mean point on the target under fixed firing conditions and exclusive of aiming and installation factors. Ballistic dispersion refers to those variations in the impact point attributable only to gun and ammunition characteristics. Some causes of ballistic dispersion are weight and surface variations between projectiles, variation in burning efficiencies, and variations in the aerodynamic forces on the projectile.

(3) Ballistic Coefficient. This is a measure of the attenuation of the velocity of a projectile or fragment in transit from the platform to the target. Ballistic coefficients are normally in approximating formulations to determine average speed or time-of-flight for the projectile.

(4) Thermal Blooming. Thermal blooming is a non-linear dispersion of electromagnetic radiation due to atmospheric index-of-refraction changes caused by molecular absorption of the propagating energy. When a beam of electromagnetic radiation passes through a gas, some of its radiant energy will be absorbed by the gas molecules and transformed into kinetic energy. The resultant temperature rise will force the gas particles away from the beam until the particle density has been reduced to the proper level for that particular temperature and pressure. If the beam is non-uniform, i.e., more intense at the center than at the edges, the resultant atmospheric density will be less at the center. Hence, the atmospheric index of refraction, which is proportional to density, will vary across the beam. Since light rays are bent away from areas of low index of refraction, a dispersion of the beam results. The magnitude of this dispersion effect depends on many factors, such as radiation wavelength, beam intensity, time of radiation in a particular direction, and the atmospheric conditions.

(5) Atmospheric Attenuation. This is the attenuation of electromagnetic radiation energy as it propagates through the atmosphere due to absorption by gases and scattering by particles.

b. Guidance Methods:

Guided propagators can be guided missiles or guided projectiles. However, since most anti-aircraft guided propagators are guided missiles, this terminology will be used here. The guided missile system contains a guidance package that attempts to keep the missile on a course that will eventually lead to an intercept with the target.

Several types of guidance are possible, and a given missile system may use more than one type. For most

anti-aircraft applications, the types include command, beam-rider, homing, and retransmission.

(1) Command Guidance. Command guided missiles are those whose guidance instructions or commands come from sources outside the missile. Figure 2.4 illustrates one example of a command guidance system. In this type of guidance, a tracking system that is separate from the missile is used to track both the missile and the target. The tracking system may consist of two separate tracking units, one for the missile and one for the aircraft, or it may consist of one tracking unit that tracks both vehicles. The tracking can be accomplished using radar, optical, laser, or infrared systems. A radar beacon or infrared flare on the tail of the missile can be used to provide missile position information to the tracking system. The target and the missile ranges, elevations, and bearings are continuously fed to a computer. Using the position and position rate information, the computer determines the flight path the missile should take that will result in a collision with the target. It compares this computed flight path with the predicted flight path of the missile based on current tracking information and determines the correction signals required to move the missile control surfaces to change the current flight path to the new one. These command guidance signals are sent to the missile receiver via the missile tracking system, a separate command link, such as a radio, or by a wire between the launching platform and the missile. Besides steering instructions, the command link may be required to transfer other instructions to the missile, such as fuze arming, receiver gain setting, and warhead detonation. The specific path along which the missile is navigated is determined by the type of guidance law used by the system. A particular type of command guidance and navigation where the missile is commanded to always lie on the

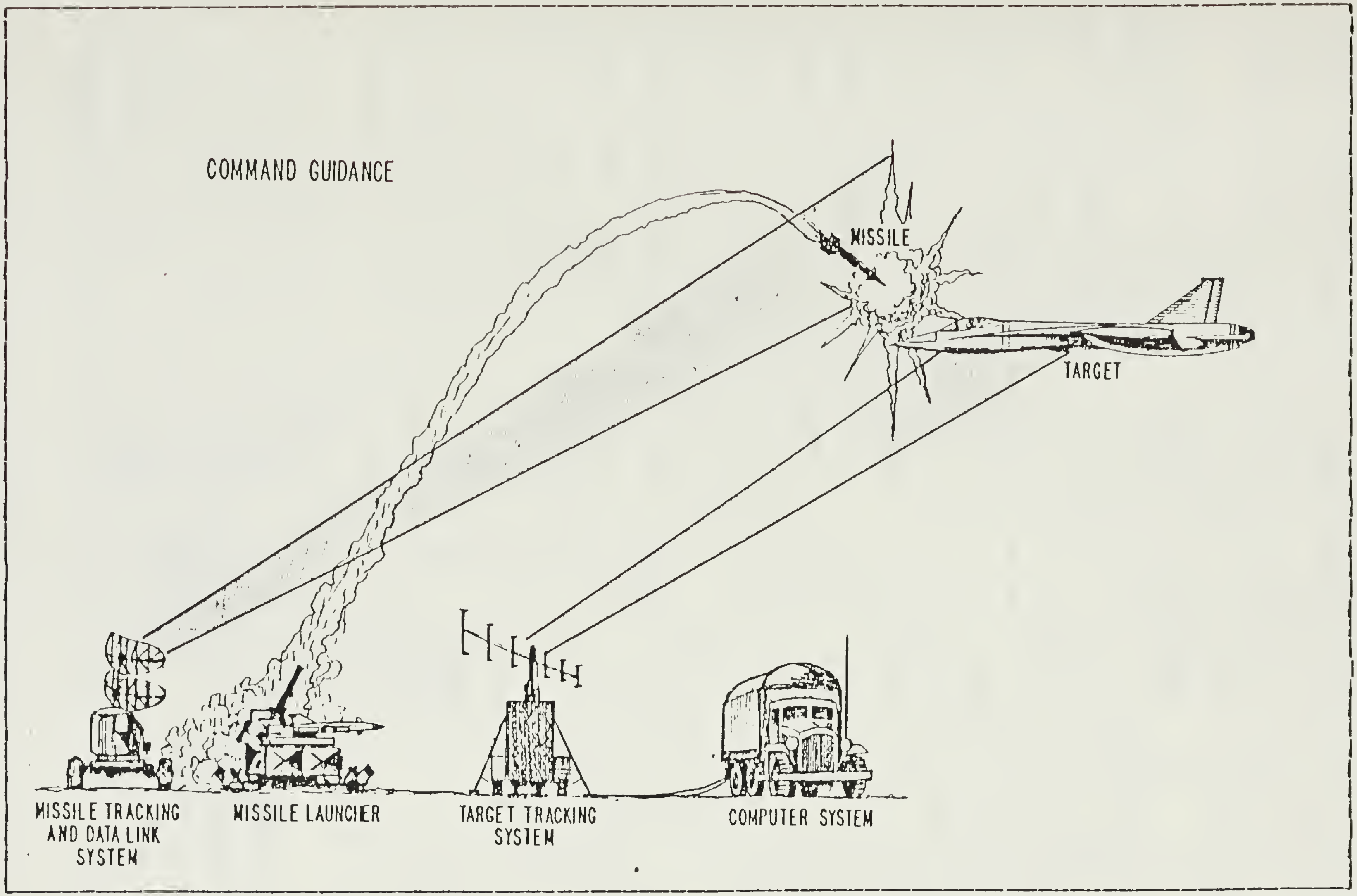

Figure 2.4 Command Guidance

line-of-sight between the tracking unit and the target is known as command-to-line-of-sight (CLOS) or three point guidance. This type of guidance is sometimes mistakenly called beam-rider guidance. Command guidance is used mostly with short range missile systems because of the relatively large tracking errors that occur at long range.

(2) Beam-rider Guidance. In the beam-rider types of guidance, illustrated in Figure 2.5, and Figure 2.6, the aircraft is tracked by an electromagnetic beam transmitted by a tracking system off-board the missile. The guidance equipment in the missile includes a rearward facing antenna that senses the target tracking beam. Steering signals that are based on the position of the missile with respect to the center of the tracking beam are computed in the missile and are sent to the control surfaces. These correction signals produce control surface movements intended to keep the missile as nearly as possible in the center of the target tracking beam. The missile can thus be said to ride the beam; it does not see the target. The narrow, pencil-like tracking beam is sometimes referred to as the guidance beam. There is usually a wider, lower power beam used to capture the missile shortly after launch, and for this reason it is referred to as the capture beam. The beam that the missile rides can either track the aircraft directly, or a computer can be used to predict the direction the missile beam should be pointing to effect an eventual collision with the target. In this situation, a separate tracker is required to track the target.

The beam-rider missile guidance has both advantages and disadvantages. It permits the launching of a large number of missiles into the same target tracking beam, since the guidance equipment is carried in the missile. This, however, causes the missile to be rather large and expensive. Furthermore the tracking beam must be reasonably

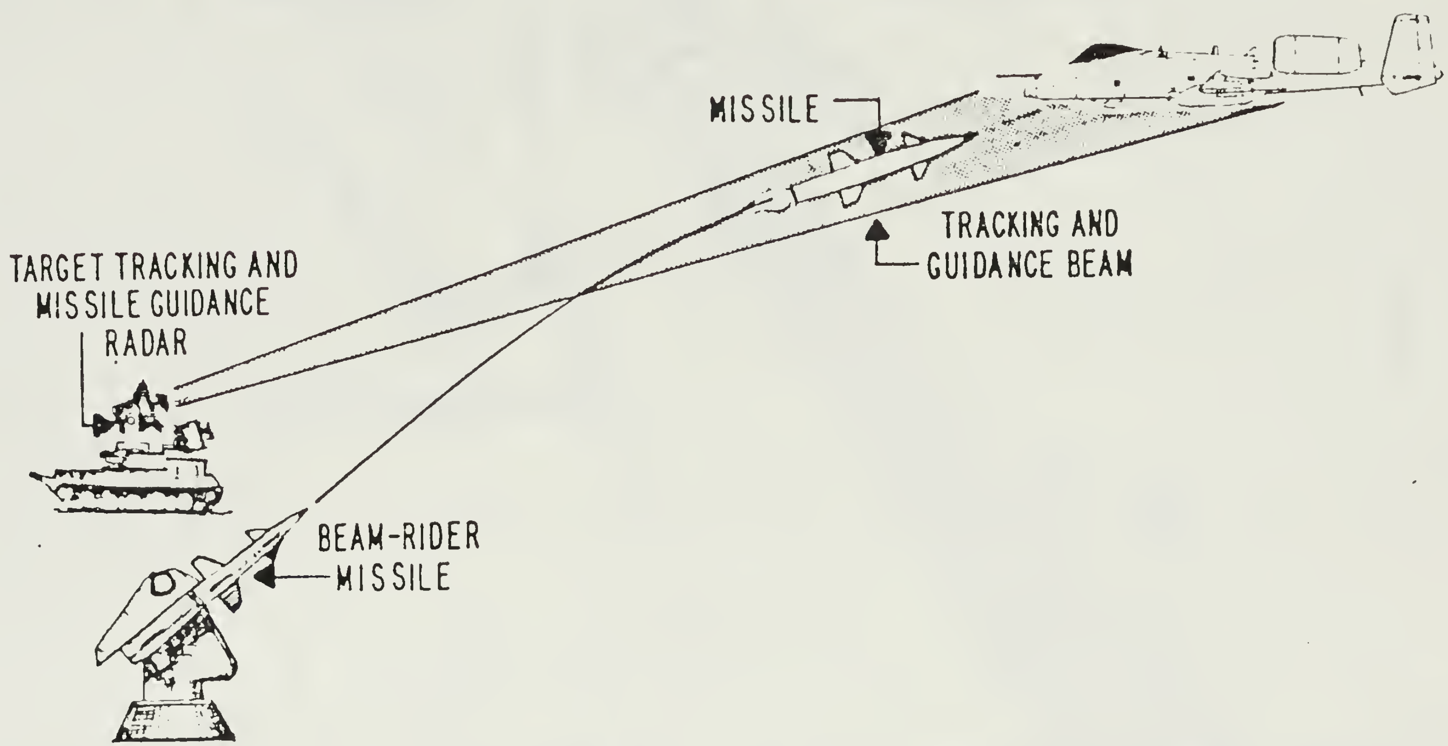

Figure 2.5   Beam-rider Single Beam Guidance

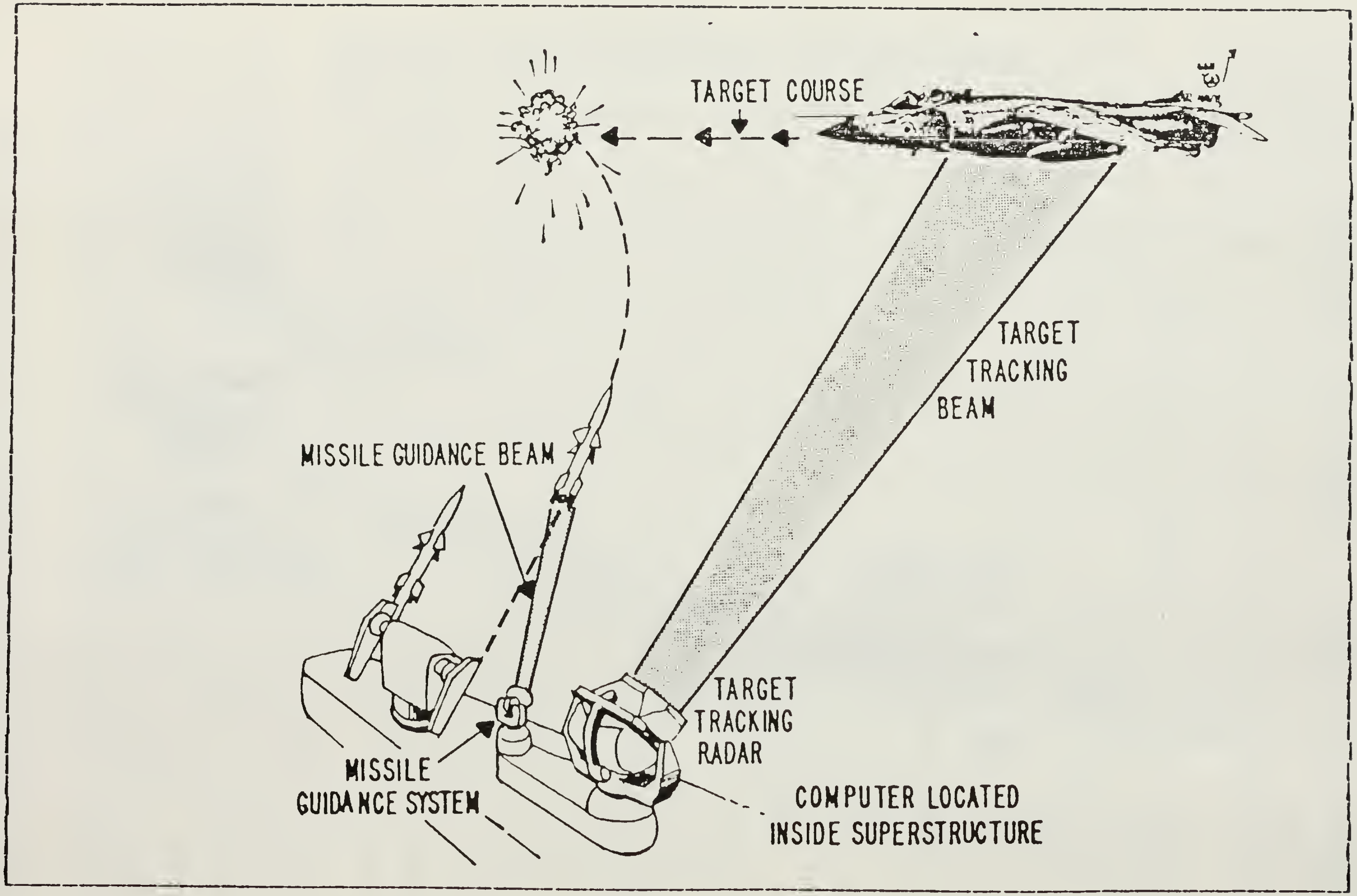

Figure 2.6 Beam-rider Dual Beam Guidance

narrow to insure an intercept, and the chance of loss of the missile due to target maneuvering and evasion is increased. The problem of large tracking error for long range targets usually restricts beam-rider missiles to short range.

(3) Homing Guidance. A homing guidance system is one that can determine the position of the target and can formulate its own commands to guide itself to intercept. With homing guidance, the tracking error is usually reduced as the missile approaches the target. There are three major types of homing systems: active, semi-active, and passive. These are illustrated in Figure 2.7.

If the aircraft is tracked by electronic radiation equipment in the missile, the system is referred to as active. An example is a system that uses a radar transmitter located on the missile to illuminate the aircraft and then uses the radar reflections from the target for guidance. A major advantage of active homing is the fact that the missile can be launched and forgotten by the firing unit with no further tracking required. This is referred to fire-and-forget or launch-and-leave. Disadvantages of active homing are the additional weight and expense for each missile and the fact that the radiation from the missile can reveal its presence.

If the aircraft is illuminated by a tracking beam from some source not on the missile, and if the beam reflections from the aircraft in the direction of the missile are used for guidance, the system is referred to as a semi-active homing (SAH) system. The missile may also require direct illumination in a rearward facing receiver for comparison with the reflected signal from the target. With this type of guidance, the aircraft may know it is being tracked, but it does not know if a missile has been launched. A SAH missile may or may not require continuous target illumination. This type of guidance has progressed

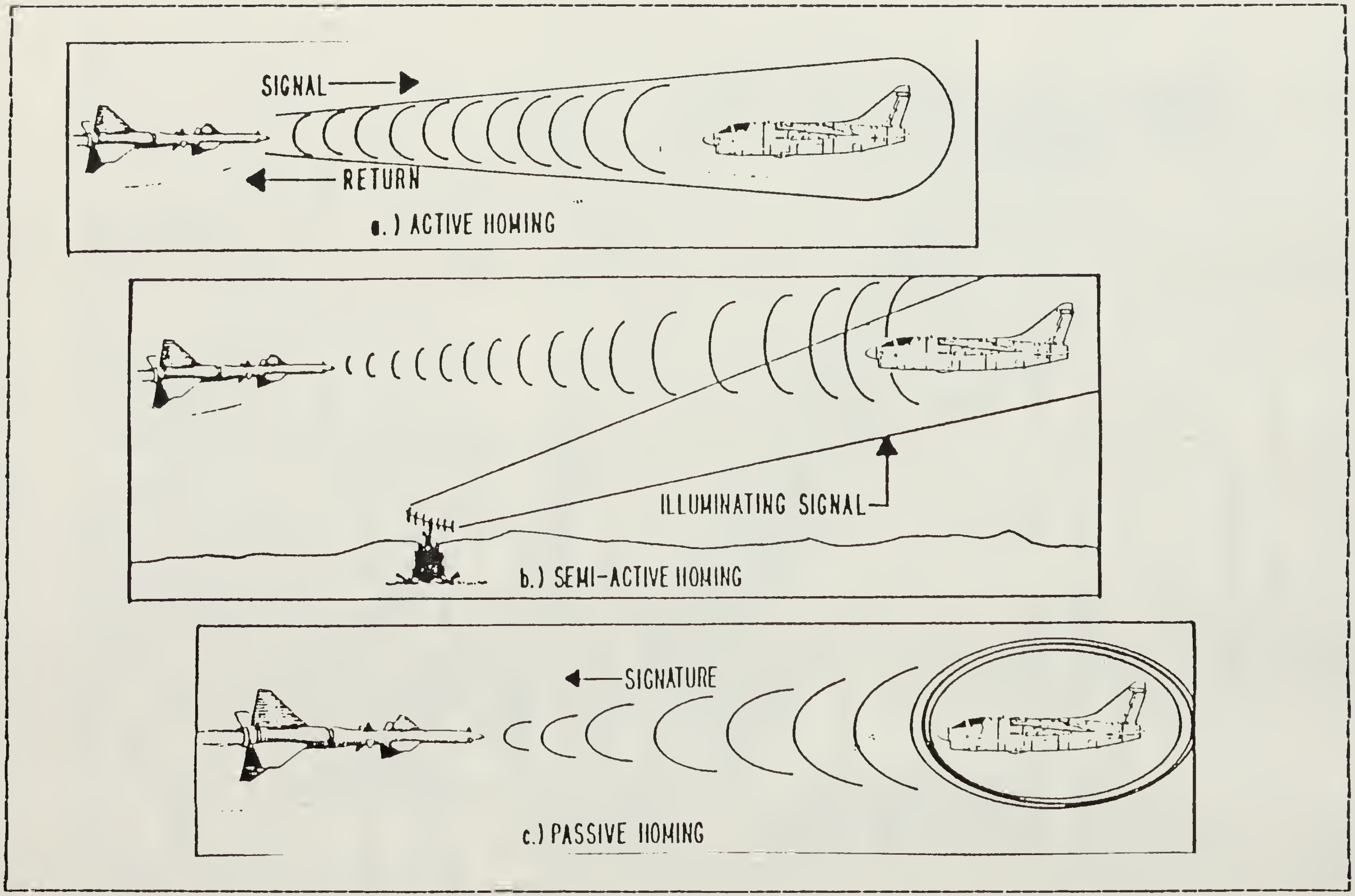

Figure 2.7 Types of Homing Guidance

from a requirement for a continuous illuminator per target to a system with a single illuminator that can track and illuminate several targets on a time-share basis. This is referred to as sample-data SAH.

Passive homing systems use electromagnetic emissions or natural reflections from the aircraft itself for guidance. One example is an infrared homing guidance system which closes in on the heat generated by the target. Another example is the anti-radiation missile that homes in on radar navigation, fire control signals, or on jamming signals emitted from the target.

(4) Retransmission Guidance. Retransmission guidance, also known as track-via-missile (TVM), is the latest technique to be used to direct missiles toward air targets. An illustration of TVM is given in Figure 2.8. Typically, a radar tracking system tracks both the target and the missile, as in command guidance. In TVM, the target tracking beam also serves as a target illuminator and a receiver on the missile detects the reflected radiation, as in semi-active homing guidance. The information on the relative target angular position gathered by the missile is relayed to a control unit. Guidance equipment at the control unit processes the echo received directly from the target and the information on target position received from the missile and determines appropriate guidance commands. The guidance commands are sent to the missile on a data link. The tracking system usually has the capability to track several targets at one time, and the control system can direct several simultaneous engagements between missiles and aircraft.

c. Guidance Phases:

Missile guidance is generally divided into three phases: boost or launch, midcourse, and terminal. The boost

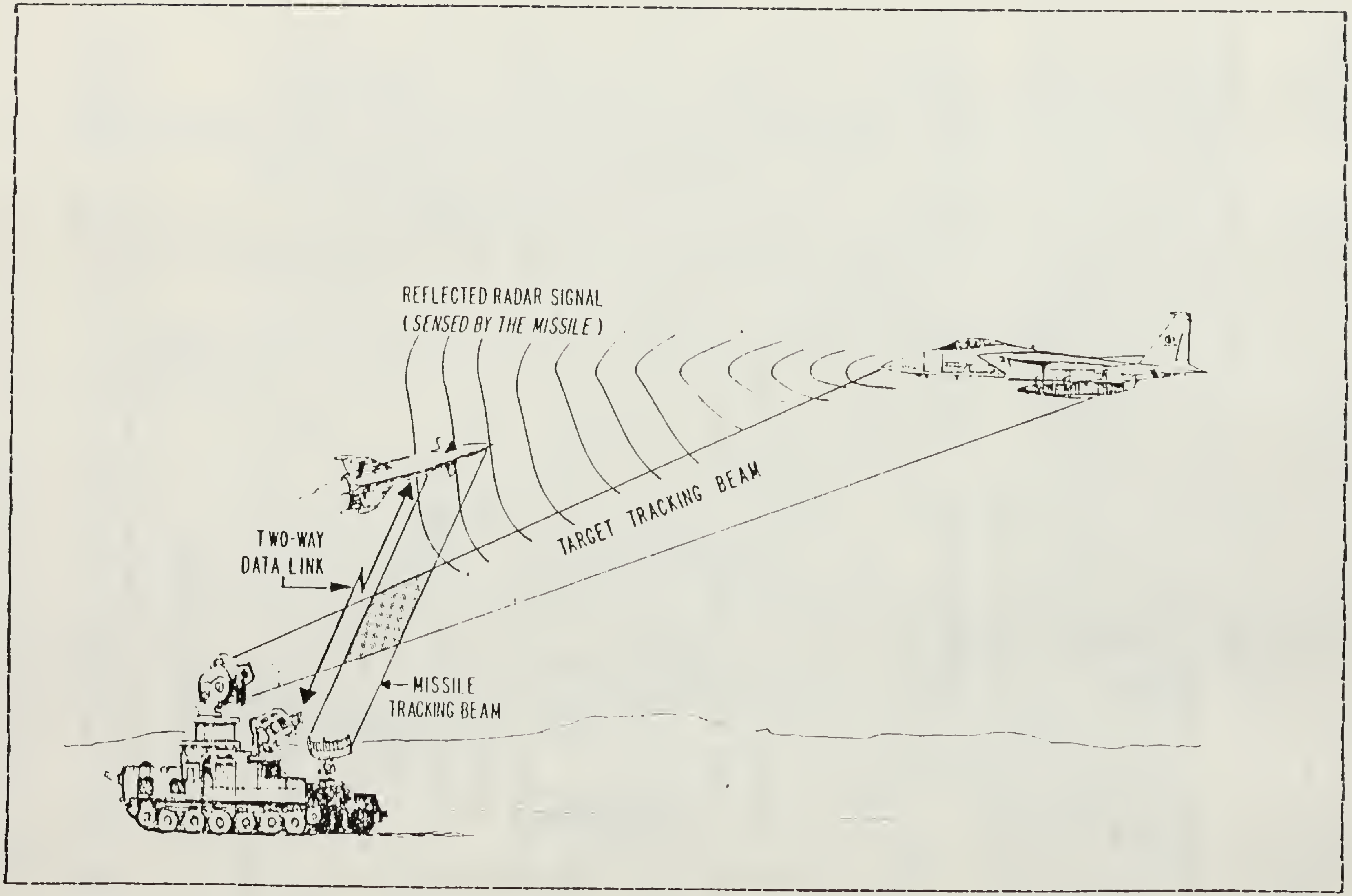

Figure 2.8 Retransmission (TVM) Guidance

phase is the period of time from missile firing until the booster burns all of its fuel. The missile may or may not be guided during this phase. The midcourse phase is usually the longest phase in both time and distance traveled. During this phase, guidance may be required to bring the missile on to the desired course and to ensure it remains on that course. The terminal phase is the last phase of guidance and must have high accuracy and fast reaction to ensure intercept with the target.

Generally, no one type of guidance is best suited for all three guidance phases. Consequently, many missile systems use more than one type of guidance, with each one operating during a certain phase of the missile trajectory. These systems are referred to as hybrid or composite guidance systems. A system may use beam-rider guidance or semi-active homing from launch until midcourse, at which time the guidance switches to active or passive homing for more accurate tracking and guidance during the terminal phase. This combination also allows the launching platform to break away from the engagement earlier than otherwise possible. Several types of guidance may also be used sequentially or simultaneously to avoid any countermeasures employed by the aircraft, such as the use of a decoy flare to draw an infrared homing system off of the radiation from the aircraft. If an active homing system is used in conjunction with a passive system, the missile may reject the flare and continue toward the target.

d. Guidance Navigation Laws:

Guidance systems can use any one of several methods or laws to navigate a missile along a trajectory or flight path. Four common laws are pursuit, lead angle, command-to-line-of-sight, and proportional navigation. The specific target flight path information required by the

guidance package depends on which law is used. Some of the most important items of information are the angle between the missile heading and the line-of-sight (LOS) from the missile to the target, the target range, and the rate of change of both the LOS angle and the range.

In the pursuit trajectory, illustrated in Figure 2.9a, the missile flies directly toward the target at all times. Thus, the line-of-sight between the missile and the aircraft is maintained essentially along the heading of the missile by the guidance system. Missiles flying a pursuit course usually end up in a tail chase situation, similar to a dog chasing a rabbit. There are two basic objections to the pursuit method. First, the maneuvers required of the missile become increasingly difficult during the last, and critical stages of flight. Second, the missile speed must be considerably greater than the aircraft speed. The sharpest curvature of the missile flight path usually occurs near the end of the flight. At this time, the missile must overtake the aircraft. If the aircraft attempts to evade, the last-minute angular acceleration requirements placed on the missile could exceed its aerodynamic capability, and thus cause a large miss distance. Near the end of the flight, the missile is usually coasting because the booster and sustainer motorthrusts last for only a short part of the flight. Consequently, more energy is required to make short radius, high speed turns at a time when the missile is losing speed and has the least turning capability. The most favorable application of the pursuit course is against slow moving aircraft, or for missiles launched from a point directly to the rear of the aircraft, or head on to an incoming aircraft.

In the lead angle or constant bearing trajectory, shown in Figure 2.9b, the guidance system directs the missile along a path that results in an eventual intercept

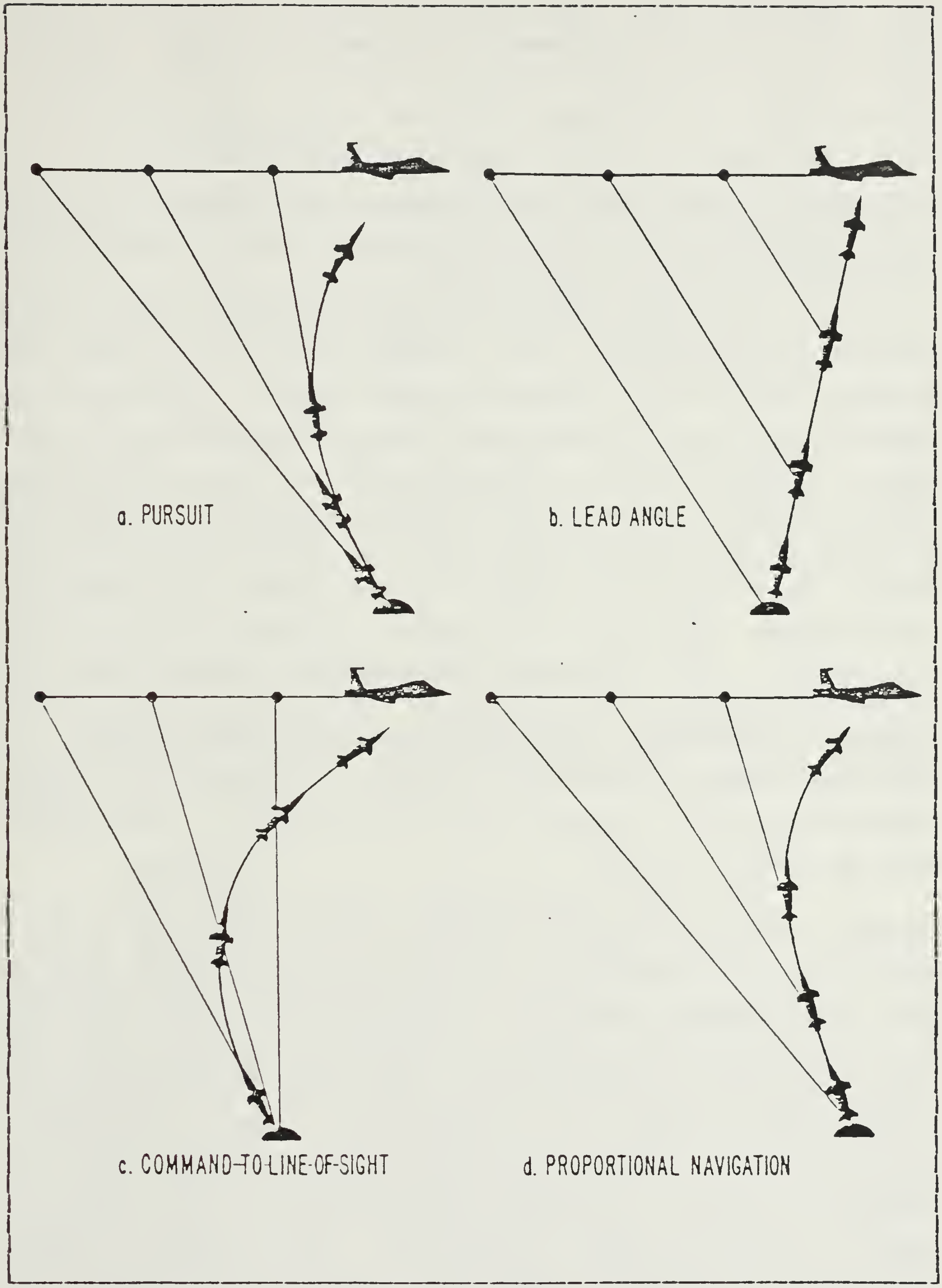

Figure 2.9 Missile Trajectories

with the aircraft. For constant-speed, non-maneuvering aircraft, the LOS between the missile and the aircraft remains at a constant angle, and the missile flies a straight line trajectory. This is often referred to as a collision course. If the aircraft changes direction, the new lead angle required for a collision is determined, based on an assumed straight line target flight path, and the missile is maneuvered to that new heading.

In the command-to-line-of-sight (CLOS), the missile is constantly being steered to lie on the line between the target tracker and the target, as shown in Figure 2.9c; thus the alternate name 3-point guidance. This type of trajectory is typically used only in short range missile systems. An example of a CLOS system is one in which the target is tracked visually, using optics, and the missile is tracked by a sensor at the tracker that observes the off-axis position of the flare located on the tail of the missile. The amount of offset of the missile from the LOS of the tracker to the target is used by the guidance system to determine the appropriate steering commands to drive the missile back to the target tracking line. These commands are then relayed to the missile over a data link, such as a wire or radio.

The most common method for changing the missile heading to cause a target intercept is proportional navigation or pro nav. In order to accomplish proportional navigation, the guidance system must be able to determine the time rate of change of the LOS between the missile and the target, as illustrated in Figure 2.9d. This can be achieved by equipment located on the missile or at the launching platform. When the launching platform equipment is used, the location of both the missile and the target must be determined. In proportional navigation, the guidance system attempts to maintain an essentially constant LOS angle, and

hence cause a collision by making the rate of change of the missile heading directly proportional to the rate of change of the LCS.

6. Final Evaluation

After a weapon has been launched and has completed its flight, the air defense system must determine if the threat has been eliminated or if the engagement should be continued. The destruction of the aircraft can be detected by observing sudden changes in the tracking status on the radar systems. Such changes as rapid loss in altitude and speed, or a sudden change in the quality of the fire control system's track, possibly showing several smaller contacts instead of a previous strong single contact will indicate target damage. Other indications may be visual, audible, or electronic.

B. ENVIRONMENTAL OPERATIONAL FACTORS

Environmental factors include the mobility of the air defense system, its locational adaptability, and its weather capability.

1. Mobility

Mobility is the ease with which an air defense system can be moved. Factors involved are the effort required for disassembling, loading, transporting, and setting up a new location so that effective firing or launching can be achieved. The measures of mobility are the operational time at one location and the down-time required to move from one operating site to another. Many gun systems and some missile systems are mounted on wheeled or tracked vehicles and can fire on the move or shortly after stopping. Sea-based air defense systems are extremely mobile and require no down-time in moving to new operational sites.

2. <u>Locational Adaptability</u>

Locational adaptability refers to the ability of an air defense system to adapt to the sites at which its operation is desired in a combat environment. Factors which must be considered in site selection are the area required, the terrain, and accessability. Sea-based systems must consider depth of water, navigation hazards such as shoals,and possibly man made hazards such as mines. Ease of entry, exit, and maneuverability are also important locational considerations for surface units.

3. <u>Weather Capability</u>

Weather capability refers to the ability of the air defense system to track and deliver the propagator to an aircraft during variations in visibility, cloud cover, light, and forms of precipitation. Generic measures of weather with respect to tracking capability are discussed below.

a. Clear Day Capable:

A clear day capable system is one with the capability to maintain track under daylight conditions with no intervening clouds and with required visibility.

b. Clear Night Capable:

A clear night capable system has the ability to maintain track with no cloud or visibility constraints, but with reduced light level (i.e., half-moon, quarter-moon, etc.).

c. Hazy Weather Capable:

A hazy weather capable tracker is qualified for day or night and has ability to cope with an increased

amount of particulate matter in the air (i.e., smoke, fog, dust, etc.).

d. All Weather Capable:

An all weather capable system has the ability to maintain track with extremely low light levels, complete cloud cover, and minimal visibility.

III. ORDNANCE PACKAGE AND DAMAGE MECHANISMS

The function of the air defense propagator is to bring the ordnance package sufficiently close to the aircraft for the purpose of inflicting damage on the designated target. The ordnance package consists of the warhead and possibly a fuze. The purpose of the warhead is to provide or generate the damage mechanisms to be delivered to the target. Consequently, the warhead is considered to be the primary focal point of the weapon. The different types of warheads can be described in terms of their configuration and ingredients. Since each classification of target presents a unique tactical situation, the selection of the warhead type is critical to ensure target destruction is optimized.

A. DAMAGE MECHANISMS

An examination of warhead types is preceded by a discussion of the damage mechanisms, damage processes, and terminal processes associated with the payloads.

1. Definitions

A damage mechanism is the output of the warhead that causes damage to the target. It is the physical description of the tangible instrument or measurable quantity designed to inflict damage upon the target. The conventional damage mechanisms are penetrators, fragments, incendiary particles, and blast. Certain missile types may utilize more than one damage mechanism in attempting to destroy a target. For example, a surface-to-air missile can have blast, fragments, and incendiary particles as its primary damage mechanisms. The missile debris caused by the warhead detonation, such as

broken control surfaces, motor case, and other miscellaneous parts, are secondary penetrator-type damage mechanisms.

A damage process refers to the interaction between the damage mechanism and the target. The conventional damage processes are ballistic impact, penetration, ignition, leading to a fire or an explosion, hydraulic ram, and blast loading. Some radiation damage processes are ignition, thermal weakening, and burn-through.

The terminal effects refer to the response or reaction of the various materials, components, and personnel in the aircraft when subjected to the damage processes. In order to make the design decisions, the engineer must be aware not only of the particular type of threat, but also of the damage processes and the terminal effects which are caused by the damage mechanisms.

2. Types of Damage Mechanisms

a. Penetrators:

The first damage mechanism to be discussed is the penetrator. A penetrator can be the core of an armor-piercing (AP) projectile, or a rod, or a shaped charge jet. The damage processes associated with the penetrator are ballistic impact, penetration, hydraulic ram, and ignition. The amount of penetration through the aircraft structure, components, and fluid is proportional to its momentum. The penetrator velocity and mass are therefore important parameters.

The primary damage processes caused by penetrators are ballistic impact and penetration. Initial penetration usually involves piercing the skin of the target. Penetrators with soft cores generally flatten upon impact and create larger holes than their initial diameter. When the penetration produces a clean hole, the section of the

structure sheared out by the penetrator is called a plug, and this type of penetration is called plugging. For slightly harder material, the penetrator must tear the surface during entry, and a crown-shaped protrusion surrounded by radial cracks is formed, as shown in Figure 3.1. This type of penetration is called petalling.

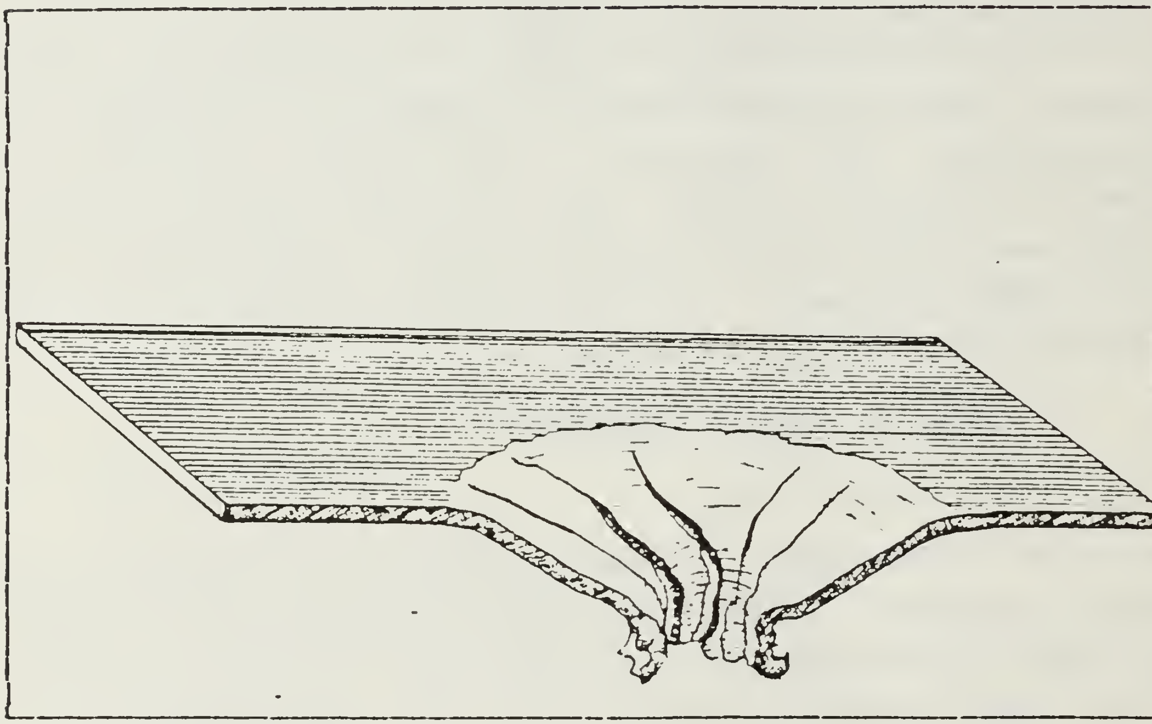

Figure 3.1 Petalling Damage

The velocity required for penetration is called the ballistic limit or V 50 ballistic limit and is that velocity at which 50% of the impacters penetrate and 50% fail to penetrate. After penetration, the particle will have a new or residual velocity, possibly a new direction, and perhaps a new mass. Several sets of penetration equations have been developed for the residual velocity, direction, and mass of penetrators and fragments impacting various materials found in aircraft.

The terminal effects of impact and penetration depend upon the element that is penetrated. In the case of structural members (e.g., spars, ribs, skin, and longerons), penetration can lead to a loss of load-carrying ability. Aerodynamic surfaces, such as ailerons and rudders, can fail to perform their aerodynamic function after penetration. Mechanical components (e.g., hydraulic actuators, control rods, and drive shafts) can crack, jam, or sever. Penetrated engine components can lead to catastrophic engine failure, fuel leakage, and engine fire. Penetration through pressure lines or fluid containers can result in leakage, hydraulic ram damage, subsequent injestion of fuel by an engine through inlet ducts, and possibly fires and explosions. Penetration through avionics components such as computers and radar equipment, can cause a loss of signal or function and may lead to a fire or explosion. Crew members, when penetrated, tend to lose their ability to function, and penetration of explosives or propellants can result in a fire or explosion.

When a penetrator impacts armor or a very hard structural material, a damage process called spallation may result. In spallation, fragments are torn off the rear surface of the structural material. These fragments then become damage mechanisms themselves.

When a penetrator enters a compartment containing a fluid, a damage process called hydraulic ram is generated. Hydraulic ram can be divided into three phases; the early shock phase, the later drag phase, and the final cavity phase. Figure 3.2 illustrates the phases of hydraulic ram. The shock phase is initiated when the projectile penetrates the wall of the container or tank and impacts the fluid. As energy is transferred to the fluid, a strong hemispherical shock wave centered at the point of impact is formed. This creates an impulsive load on the inside of the

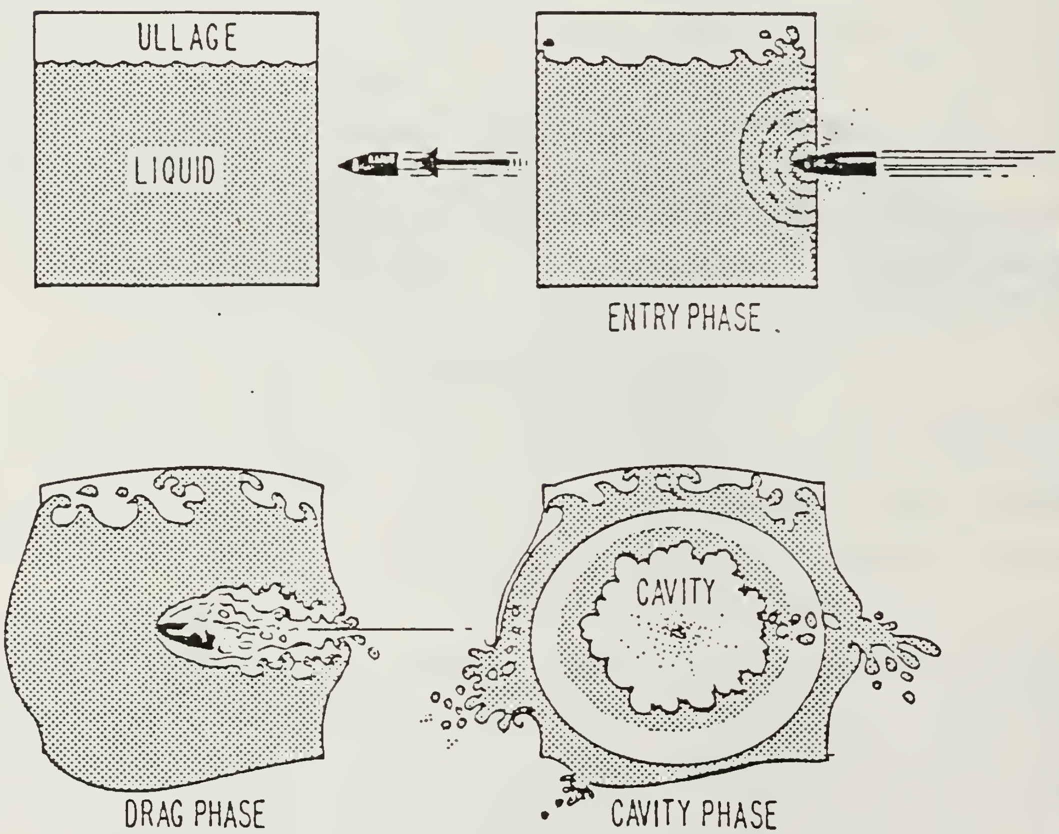

Figure 3.2 Hydraulic Ram

entry wall in the vicinity of the entry hole which may cause the entry wall to crack and petal. As the projectile travels through the fluid, it usually tumbles, and its potential energy will be transformed into kinetic energy. The projectile will slow down due to viscous drag. An outwardly propagating pressure field is generated as fluid is displaced from the projectile path. In contrast to the pressures developed in the shock phase, the fluid is accelerated slowly so that the peak pressure is much lower, however the duration of the pressure pulse is considerably longer. A cavity develops behind the projectile as it passes through the fluid. The cavity is filled with liquid vapor evaporated from the cavity surface and with air that has entered through the entry hole. As the fluid seeks to regain its undisturbed condition, the cavity will oscillate. The concomitant pressures will pump fluid from any holes in the tank, and they may be sufficient to damage other system components. The cavity oscillation is called the cavity phase.

The hydraulic ram loading on all of the wet walls of the tank can cause large scale tearing and petalling. These holes may be much larger than those caused by the actual penetrator. The hydraulic ram loading can also be transmitted through attached lines causing failure at fittings or other discontinuities.

A metal penetrator that impacts a metal target at high velocity may generate incandescent particles or vapors that are a source for ignition of flammable gasses or combustible materials. This phenomenon is referred to as vaporific flash.

b. Fragments:

Fragments are a damage mechanism which can be described as irregular metal particles varying in weight, shape, and velocity. The difference between a penetrator and

a fragment is the relative size, shape, and number produced. Fragment weight is usually expressed in grains (1 gram = 15.4 grains). They may be produced either by detonation of an explosive warhead, or by ballistic impact.

Blast-generated fragments result from the detonation of high explosive (HE) warheads.They are usually constructed of steel and weigh between 30 and 200 grains. Their shape may be cubic, diamond, parallelpiped, or random. Their total initial velocity can vary from 4,000 to 10,000 feet per second, depending upon the HE type, the ratio of case weight to charge weight, and the missile velocity. Depending upon the fuzing technique employed,the detonation may occur either inside or outside the aircraft. The size, momentum, and pattern of blast-generated fragments can be controlled by the warhead design to most effectively damage a specific type of target. The damage processes and terminal effects associated with blast-generated fragments are similar to those of the penetrator previously discussed. The damage caused by the fragments are generally more severe than that caused by penetrators particularly when the fragments are closely spaced. Cracks can occur between the holes caused by the fragments, compounding the extent of the damage.

Impact-generated fragments may occur either as spallation of the target material or by a break-up of the weapon at the impact point. Hard materials which resist penetration are particularly conducive to spallation. High speed impact by a damage mechanism, such as a fragment or penetrator,generates an internal compression stress wave in the damage mechanism and in the target. Interaction within the target material between the initial compression wave and reflected tensile stress waves off of free surfaces can cause high tensile stresses. These tensile stresses can cause pieces of the target material to be ejected from the

rear surface at high (lethal) velocities. If the damage mechanism is brittle, stresses within the mechanism itself can reach values sufficient to shatter the mechanism after striking a hard surface. In both cases, high velocity fragments can be ejected inside the aircraft with the capability to generate the same damage processes as a penetrator. Impact-generated fragments also tend to disperse randomly from the point of impact, and therefore cause damage over a greater area than does a single penetrating round.

c. Incendiary Particles:

Incendiary particles are damage mechanisms which include those chemical agents designed to cause combustion, and may be added as a filler agent to certain warheads. In an HE warhead, the incendiary material is ignited when the warhead is detonated and is dispersed by the explosion. Incendiary particles may also be generated by the high speed impact of a metal penetrator or fragment on a metal surface of the target. The damage process associated with incendiaries is ignition. Ignition may be followed by a fire or an explosion.

The effectiveness and wide use of incendiaries in anti-aircraft weapon systems stems from the vulnerability of the aircraft fuel system to fire. Ignition and subsequent fire may take place within the ullage or vapor space of a fuel tank. Fires can also occur in conjunction with a penetration damage process in which fuel spills out of holes punched in tanks by penetrators or fragments and into adjacent void areas or dry bays. Incendiary particles igniting the vapors from these spilled fuels can lead to eventual loss of the aircraft due to the fire burning through the structure, control rods, etc. Fuel is not the only flammable material on-board an aircraft. Incendiary particles can initiate fires in any combustible material such as hydraulic fluid, or in gases such as vaporizing liquid oxygen.

Under certain conditions, an explosion or detonation of a fuel-air mixture by incendiary particles can occur. This depends primarily on the composition of the fuel-air mixture and the intensity of the ignition source. Fuel vapor detonated within a fuel tank ullage can cause tank rupture, structure damage, or complete aircraft disintegration.

d. Blast:

The final damage mechanism to be discussed is blast. Blast is the rapid movement of a spherically shaped pressure wave away from the center of high pressure, as in an explosion. A typical pressure wave is shown in Figure 3.3. The pressure in the blast above the ambient pressure is called the overpressure, and the peak overpressure occurs at the leading edge of the wave.

The damage process associated with blast is called blast loading. Blast loading is the stress or pressure loading applied to a target as a result of the blast. Blast loading is the combined effect of dynamic pressure loading (drag) and overpressure loading. In most warheads, blast is a secondary damage mechanism. Except in close detonations, blast is usually the last damage mechanism to reach the target. If the pressure loading is sufficiently intense to significantly damage the target, the other damage mechanisms probably obtained a target kill, provided they hit the target.

Dynamic loading is produced by the velocity of the air in the blast with respect to the aircraft. This damage process causes structural deformation, bending, and tearing of cantilevered structures (wings), and dynamic removal of any loosely secured attachments (e.g., canopy, panels, and antennae).

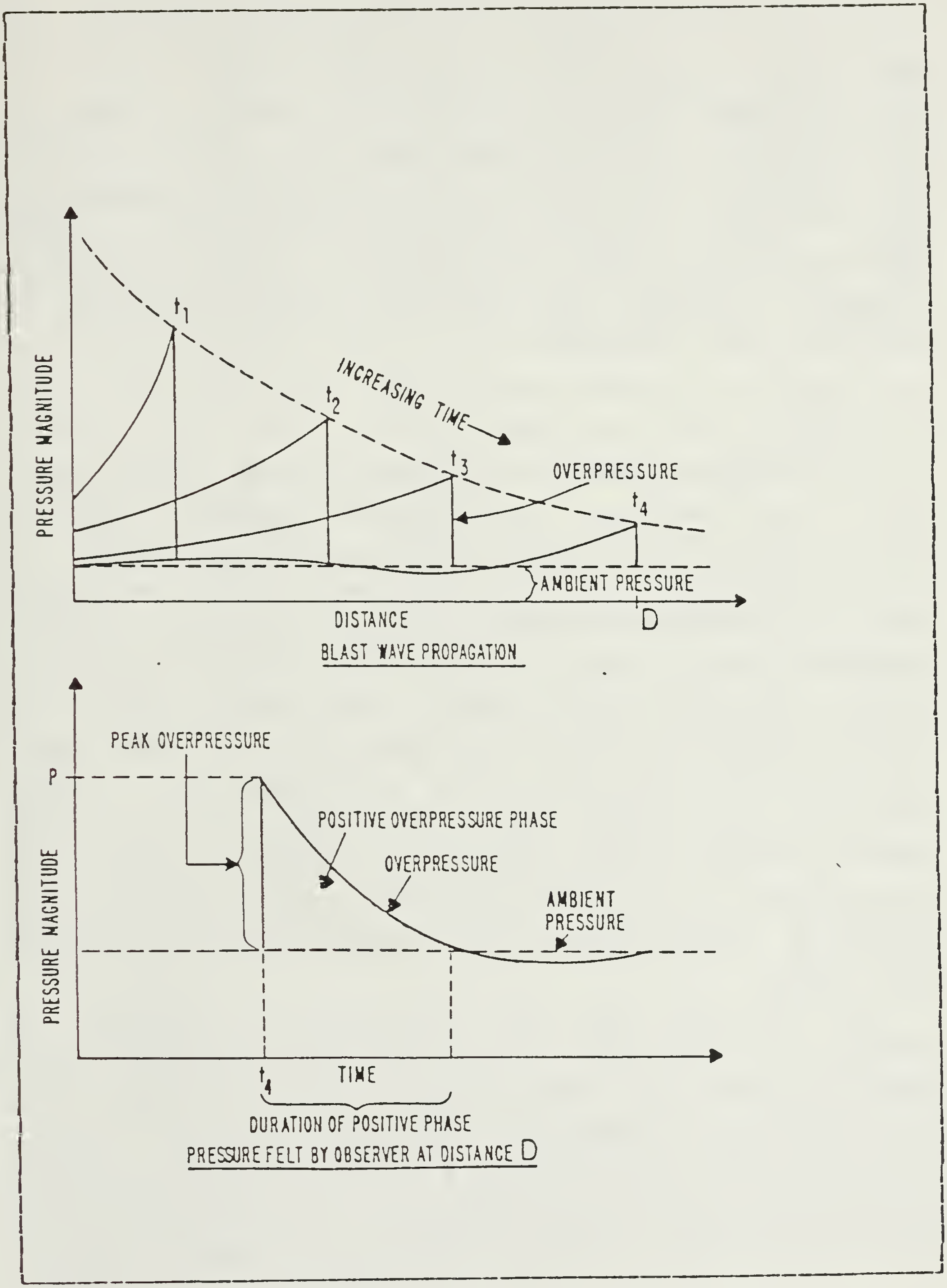

Figure 3.3 Typical Pressure Wave

Overpressure loading is a damage process that results from the effects of the overpressure in the blast striking and moving over the surfaces of the target. The initial overpressure is eventually followed by a period of underpressure. Any semi-closed structures or containers in the aircraft, such as fuel tanks and hydraulic reservoirs, can experience a sudden compression/decompression cycle. This cycle can result in structural failure or loss of integrity in these structures even though they were not directly facing the blast.

B. FUZING

The ordnance package is divided into two basic categories: fuzed warheads, and non-fuzed warheads. The fuze package consists of a safety and arming device to keep the weapon safe until it is deployed and clear of friendly forces, a detonator to initiate the high explosive charge, a device that senses the presense of the target, known as a target detection device (TDD), and a logic circuit to initiate the detonation at the proper time. To be effective, the detonation should occur at the point of the flight that will cause maximum damage to the target. This "optimum time of detonation" is a function of the flight geometry and target type. It is often desirable to delay arming of the warhead to prevent accidental detonation due to incorrect fuze action.

The fuze must have the capability to determine the proper detonation point. The data required for this calculation may be developed from energy generated by the target or from the flight parameters of the missile itself. The data may be obtained independently or it may be supplied through the guidance system of the missile. The complexity of the fuze may vary from a rather simple contact-sensing device to

one which may solve the entire fire control problem to determine the correct detonation time.

Fuzing can be accomplished by several methods. The simplest of these are the timed and contact fuzes associated with the light AAA. Timed fuzes are set to detonate at a predetermined elapsed time after firing. Contact fuzes may detonate the charge instantaneously upon target contact (superquick), or after a short delay. The type of fuze chosen will depend upon whether the detonation is desired on the external surface or within the target. High explosive projectiles used for light AAA are normally designed to be contact fuzed with a preset detonation delay because the small amount of explosive used can only be effective when detonated inside the aircraft.

Proximity fuzing, sometimes referred to as VT fuzing (a code name used during World War II for variable time fuzing), is normally used in conjunction with heavy AAA and missile warheads. With proximity fuzing, the warhead is detonated at some distance from the aircraft based upon the fuze logic and the relative location and motion of the target. The presense of the target is determined by a target detection device (TDD). The fuze TDD may be active, semi-active, or passive. The active TDD radiates an electromagnetic signal, a portion of which is reflected by the target and detected by the TDD. A semi-active TDD detects electromagnetic energy reflected from a target that is being illuminated by another source. A passive TDD detects electromagnetic energy that is radiated by the target itself. Most proximity-fuzed warheads also have time and contact fuze capabilities for self destruction and detonation upon direct hits. Some missile warheads can be command detonated by radio signals from the missile controller when the non-terminal tracking and guidance equipment indicate sufficient proximity to the target.

Non-fuzed warheads are referred to as penetrator warheads or kinetic energy penetrators and only cause damage when direct contact is made with the target. Warheads of this type are employed almost exclusively by small arms and light AAA weapons.

The safety and arming (S&A) device has two functions. First, it prevents accidental detonation of the warhead by interrupting the path between the fuze and the payload until a "safe" time. Secondly, it provides the detonation path by removing the interrupter after the the safe time has elapsed. The S&A device thus acts as a switch which remains open until safe detonation can occur and then closes to complete the detonation path. Normally, a physical obstruction is utilized to accomplish the safety and arming function.

In some cases the S&A device is used as a safety device that will self destruct the missile by initiating a destructive charge if the target is not encountered in a reasonable time frame.

C. WARHEADS

The warhead, or payload, is the damage producing element of the ordnance package. The damage may be created by converting a potential energy in the form of chemical, mechanical, or nuclear products into a destructive force. This destructive force can be an immense explosion or a release of chemical, biological, or radiological agents. The appropriate warhead is determined by the anticipated target characteristics.

Warheads are generally categorized by the type of destructive agent or damage mechanism employed in destroying the target.

1. <u>Penetrator Warheads</u>

a. Ball-Type Projectiles (B):

These projectiles contain penetrators with relatively soft metal cores designed for small weapons against personnel and unarmored targets. The soft core flattens upon impact, creating a larger hole than would normally be made by a harder substance of similar size and shape.

b. Armor-Piercing Projectiles (AP):

The armor-piercing projectile is composed of a hardened steel core encased in a metal jacket. It is shaped in such a manner as to give it maximum penetrablity through the target. This type of projectile is normally associated with small arms and light AAA.

c. Armor-Piercing Incendiary Projectiles (AP-I):

This type of projectile is the same as the armor-piercing projectile, except that an incendiary mixture has been installed inside the nose of the metal casing. The metal jacket is designed to peel off upon impact with the aircraft. The heat that is generated on impact ignites the mixture, and causes an intense, long-lasting fireball. This increases the probability of inducing a fire or explosion. These projectiles are normally associated with small arms and light AAA.

2. <u>High Explosive (HE) Warheads</u>

A high explosive warhead consists of a metal casing around a high explosive core. All high explosive warheads types are fuzed, and some may contain incendiary particles that are ignited upon impact or detonation. They may be used either in projectiles or in missiles. HE warheads can be detonated by any of the fuzing methods previously discussed.

There are four major types of HE warheads used against aircraft. They are the blast or pressure warhead, the fragmentation warhead, the continuous rod warhead, and the shaped charge warhead.

a. Blast or Pressure Warhead:

In the blast warhead, the case surrounding the HE charge is relatively thin. The primary damage mechanism is the expanding, spherically shaped blast wave produced by the detonation of the HE charge. The target is destroyed because of its inability to withstand the overpressure created by the blast wave. The overpressure wave is followed by an underpressure wave which also causes structural damage. The blast warhead generally has a small radius of effectiveness due to the small amount of charge weight and to the rapid reduction of the pressure with distance from the detonation. As the pressure expands spherically outward from the blast, it decreases as the volume of the sphere increases. The energy density decreases inversely with the volume in which it is contained, therefore the blast pressure must decrease approximately as the inverse cube of the sphere radius. The attenuation factor is actually greater than this theoretical value because of cooling effects and non-ideal expansion. Because of this large attenuation, most aerial target HE warheads are used to break the case of the warhead into many high velocity fragments, rods, and penetrators. These particles then become primary damage mechanisms.

b. Fragmentation Warheads:

Many of the current aerial warheads are designed to kill the target with fragments. A fragmentation warhead emits a maximum number of fragments at a specified velocity. The HE core is designed to break into hundreds or thousands

of fragments upon detonation. These fragments are ejected at high velocities in a narrow spherically shaped band. The amount of damage which these fragments can cause is dependent upon size, velocity, and distribution. The natural fragmentation of a smooth case is random in size. A case which breaks into tiny particles or into a few large pieces is not efficient in causing damage to the target. The large fragments could cause severe damage, but their probability of hitting the target is minimal. The small particles probably would not cause significant damage even if they did make contact with the target. For these reasons, fragment cases are often designed to break up into fragments of a particular size and shape. The fragment size would be dependent upon the type of target expected to be encountered. These cases are referred to as controlled fragmentation cases. The desired fragment dimensions can be obtained by scoring or grooving the inner or outer surfaces of the case, or by wrapping the case with wire. Some cases are composed of preformed fragments, such as steel cubes, blocks, or small rods that are buried in a plastic matrix. Examples of controlled fragmentation are shown in Figure 3.4.

Fragment density is an important parameter in considering the damage capabilities of the fragmentation warhead. Consider a warhead that produces an expanding spherical shell of fragments of the same thickness. The surface area of this shell increases proportional to its radius, and the fragment density will decrease approximately proportional to the inverse of the square of the radius. Actual warheads have even more attenuation due to drag forces and variations in fragment size. In comparing the attenuation effects of a blast warhead, it is shown that a fragmentation warhead can have a greater miss distance and still remain effective.

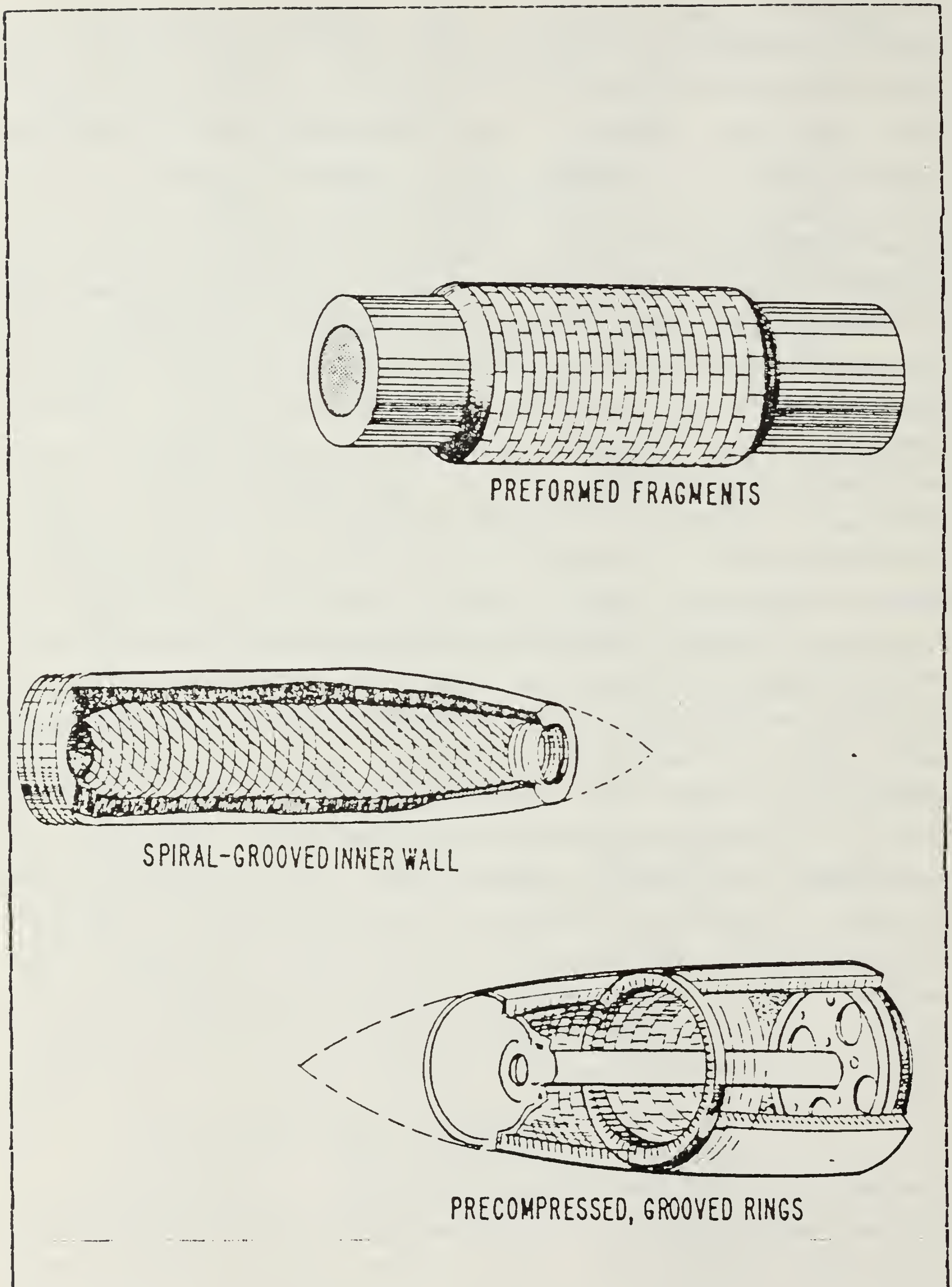

Figure 3.4 Controlled Fragment Warheads

A fragmentation warhead can be designed to emit a majority of its fragments in a particular direction. When this emission is properly aimed, the warhead can be considerably more effective than the isotropically distributed fragmentation warhead. This concentration of fragments is referred to as a focused fragment warhead.

As stated earlier, a fragmentation warhead is designed to emit fragments at a specific velocity. The attenuation of the fragment velocity is considerably less than that associated with the velocity of the expanding blast volume. The difference in velocities is due to the fragment having a constant cross-sectional area, while the surface of the blast increases as the square of the distance. Consequently, the blast lags behind the fragments.

The design of this type of warhead requires a knowledge of fragmentation propagation. Terminal ballistic studies describe the laws governing the velocity, size, shape and distribution of fragmentation warheads. Approximately forty percent of the energy produced by a warhead detonation is absorbed in the fragmentation process, while the remainder is used to establish the shock front. The fragments generated are propelled a very short distance at a high velocity. The fragments then pass through the shock wave. The initial velocity of the fragments can be estimated using the Gurney Equation.

$$V = (\sqrt{2E}) \left[\frac{C/M}{1 + 1/2\,(C/M)} \right]^{1/2}$$

where V = Initial fragment velocity (ft/sec)

$\sqrt{2E}$ = Gurney's constant (ft/sec)

C = Explosive weight (grams)

M = Case weight (grams)

The Gurney constant is determined experimentally, and differs according to the explosive type used. The best way to achieve high initial velocities is to have a high charge-to-mass ratio. This may be obtained by using a thin wall container. When a thick wall is required to withstand setback forces or to produce larger fragments, a more powerful explosive must be used. Velocities of fragments from an air burst are higher than those produced by a warhead that detonates upon impact. This is because of the additional velocity imparted to the fragments from the moving missile. This is the reason that proximity or timed fuzing provides more effective fragmentation.

c. Continuous Rod Warheads:

The continuous rod warhead consists of a bundle of rods running length-wise around the circumference of the case as illustrated in Figure 3.5. The rods are welded together at alternate ends so that upon detonation of the charge, the bundle will expand away from the blast center. The blast is sufficient to project the rods radially outward to form a large jagged ring shown in Figure 3.6. The ring will expand to about 80% of its maximum perimeter. The rods are the damage mechanism and are particularly effective against aircraft supports and structures. The initial velocity of the rods is roughly half of that associated with the fragments in the fragmentation warhead. The restricted effective area of the continuous rod warhead, perpendicular to the axis of the charge, limits the probability of striking a target.

d. Shaped Charge Warheads:

The shaped charge warheads are specifically designed to utilize a special geometry of the explosive charge and liner to focus the energy of the explosion in one

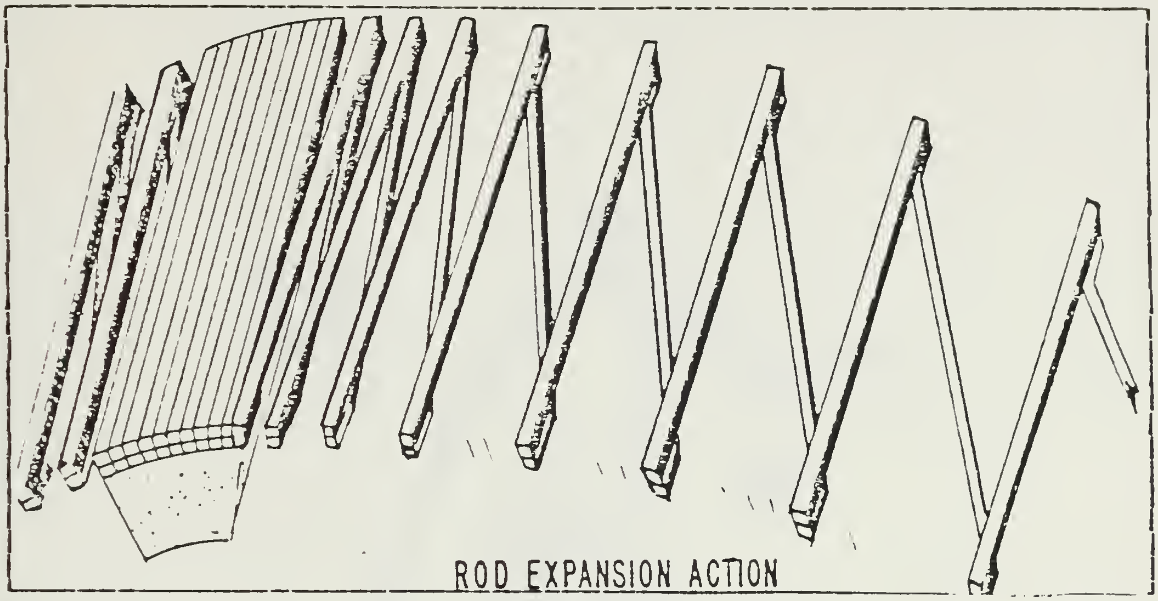

Figure 3.5 Continuous Rod Warhead

or more preferred directions. These warheads are used primarily to penetrate armor, but differ from the armor-piercing warheads in the method of operation. The armor piercing warhead is designed to force its way into the interior of the target and explode to cause further damage. The undeformed core is the primary damage mechanism. For the shaped charge, the warhead remains on the outer surface of the target and produces a destructive jet which pierces the aircraft. The focusing of energy hydrodynamically creates one or more high velocity jets and slugs of molten liner material which can cause much deeper target penetration. This energy can be focused along the warhead axis (a conical shaped charge) or in a desired array (a linear or multi-shaped charge) to increase the number of jets. Shaped charge warheads designed for aircraft are generally multi-shaped. Figure 3.7 illustrates a typical shaped charge warhead.

A shaped charge warhead consists of four basic components. The first is a thick-walled explosive-filled case

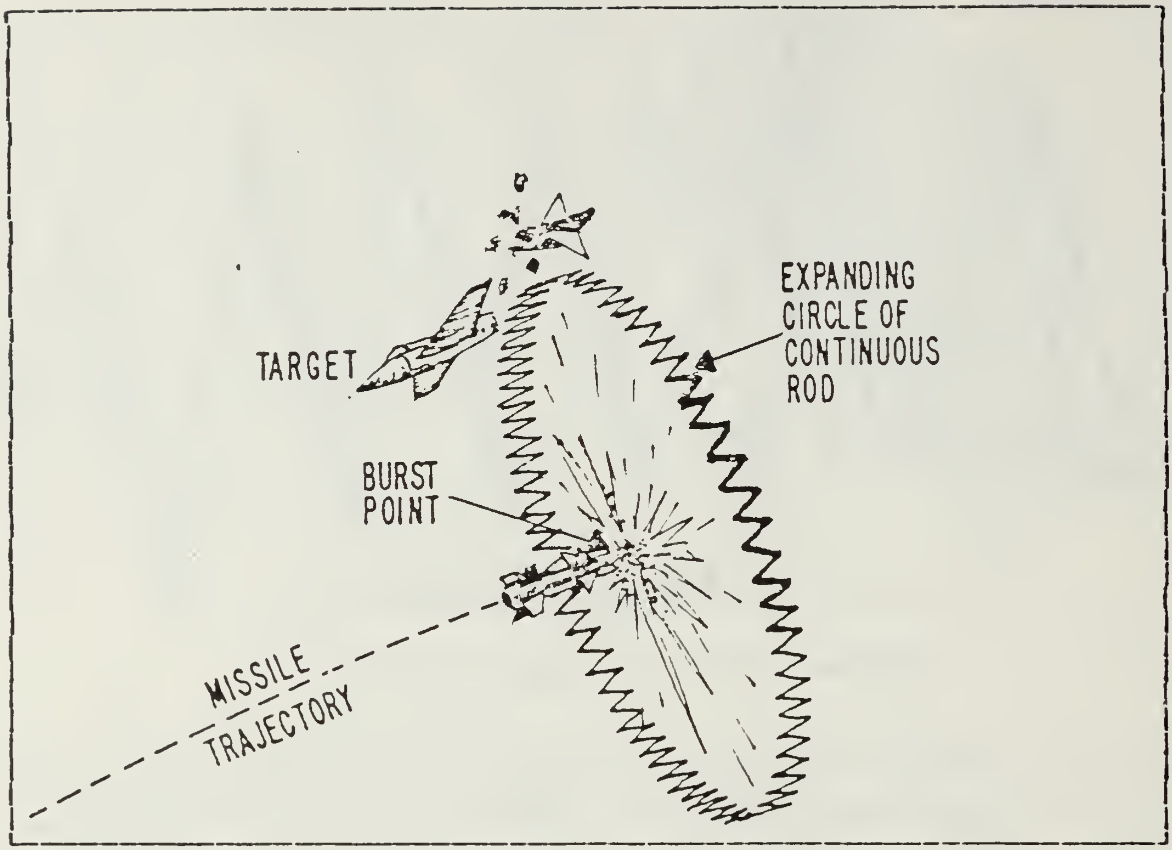

Figure 3.6 The Expanding Rods

that is open in the front.The other components are: a thin front liner, a fuze, and a detonating device. A thin nose cone allows for proper aerodynamic stability.

When a jet strikes a target, immense pressures are produced at the point of contact. This pressure causes stresses far above the yield strength of the steel and the target material flows out of the path of the jet as a fluid. Because of the large radial momentum associated with the flow of the target material, the diameter of the hole produced is considerably larger than that of the jet. As the jet particles strike the target, they are carried radially along with the target material. Thus, the jet is used up as it travels through the target. The jet does not spread out

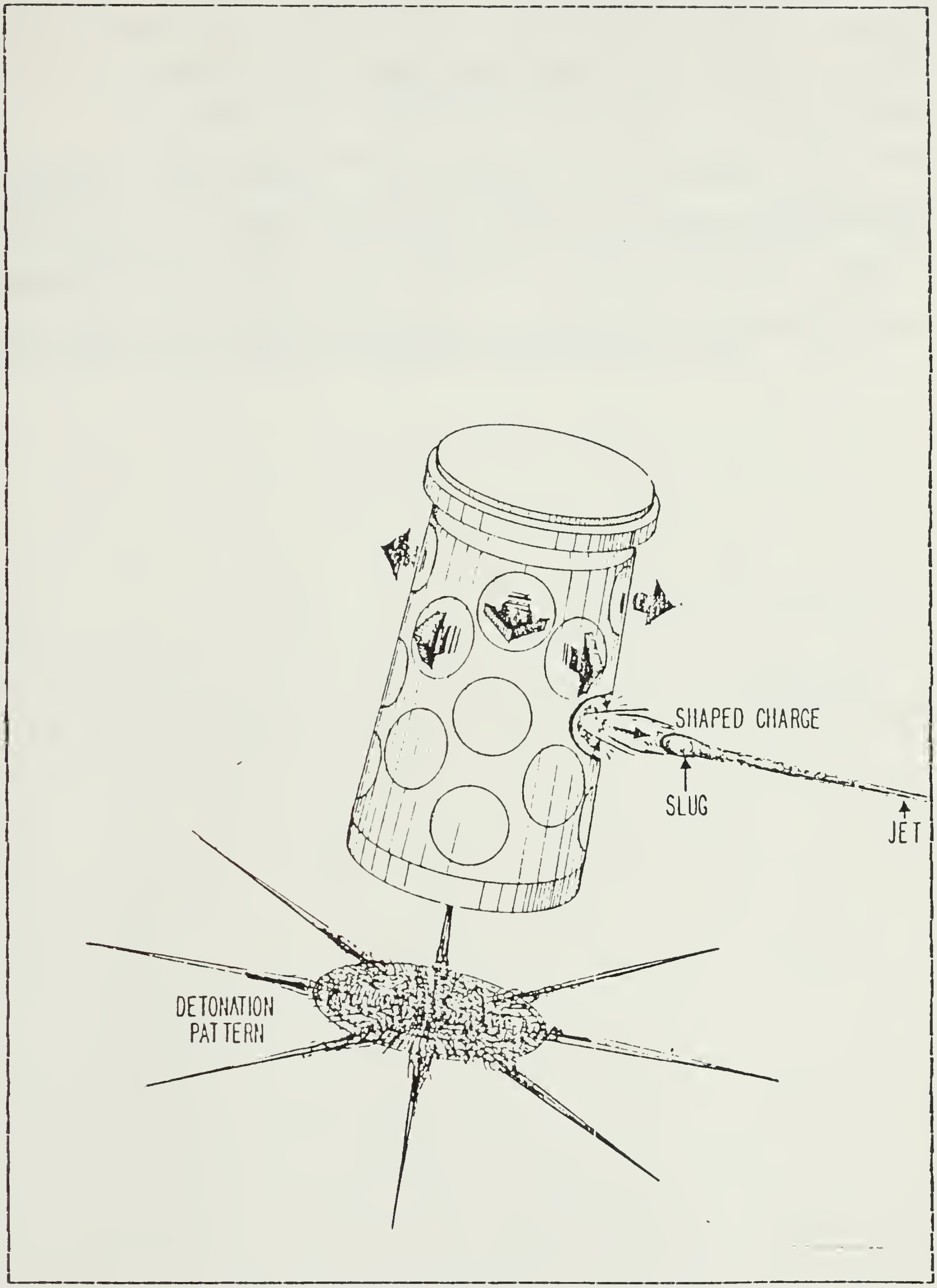

Figure 3.7 Typical Shaped Charge Warhead

in a cone shaped spray as it exits from an armor shielding. If the jet has enough energy to spare after perforating the armor, it will continue along its original path and may cause further damage such as fire and explosions.

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